Weather constraints guide energy storage and heat pump opportunities

Jacqueline A. Dowling

Postdoctoral Energy Fellow
Stanford University

Past: Caltech PhD on
Long-Duration Energy Storage

Future: Assistant Prof at University of Iowa
in Civil & Environmental Engineering

Analyze resource constraints. Guide technology innovation. Target decarbonization solutions.

Stanford University

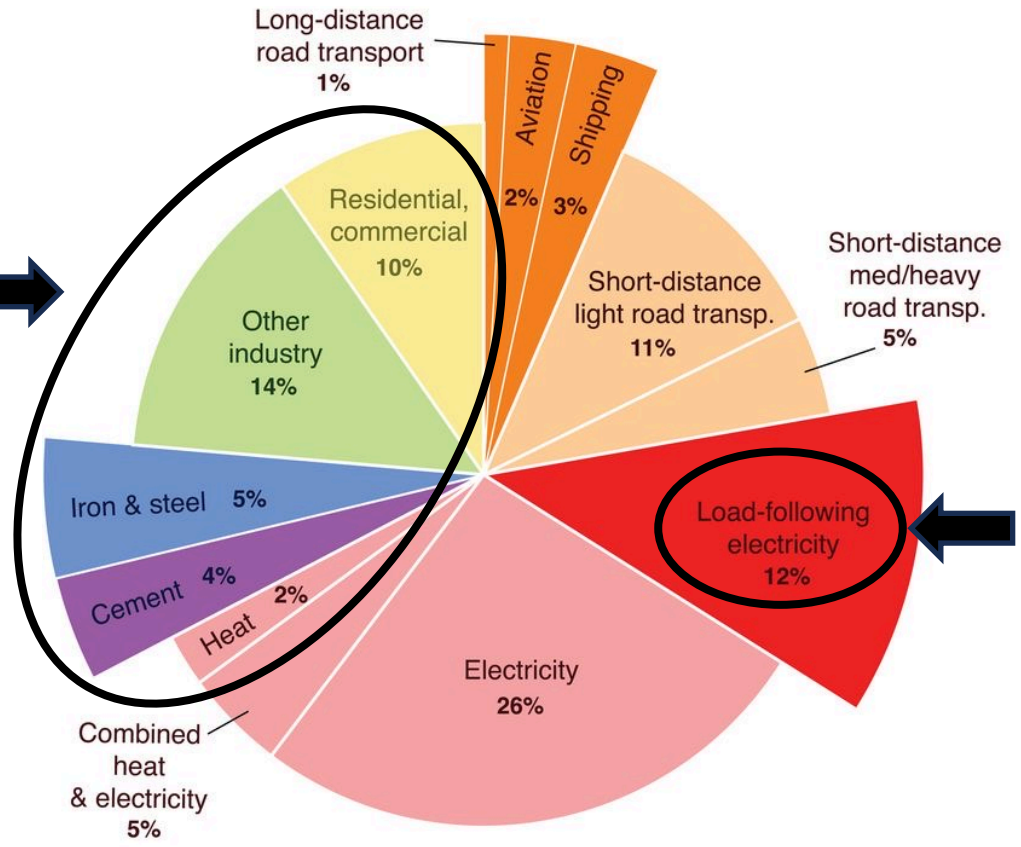
Stanford Sustainable Solutions Lab

Solving the Clean Energy Challenge

Postdoc work

Net-zero emissions heat

40% of global emissions



A **Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)**

PhD work

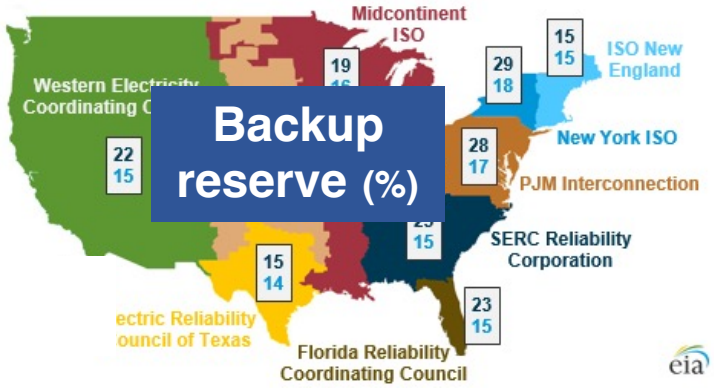
Load-following electricity ★

12% of global emissions

Davis et al., Net-Zero Emissions Energy Systems. *Science,* **2018**.

Blackouts are deadly and electricity reliability is key

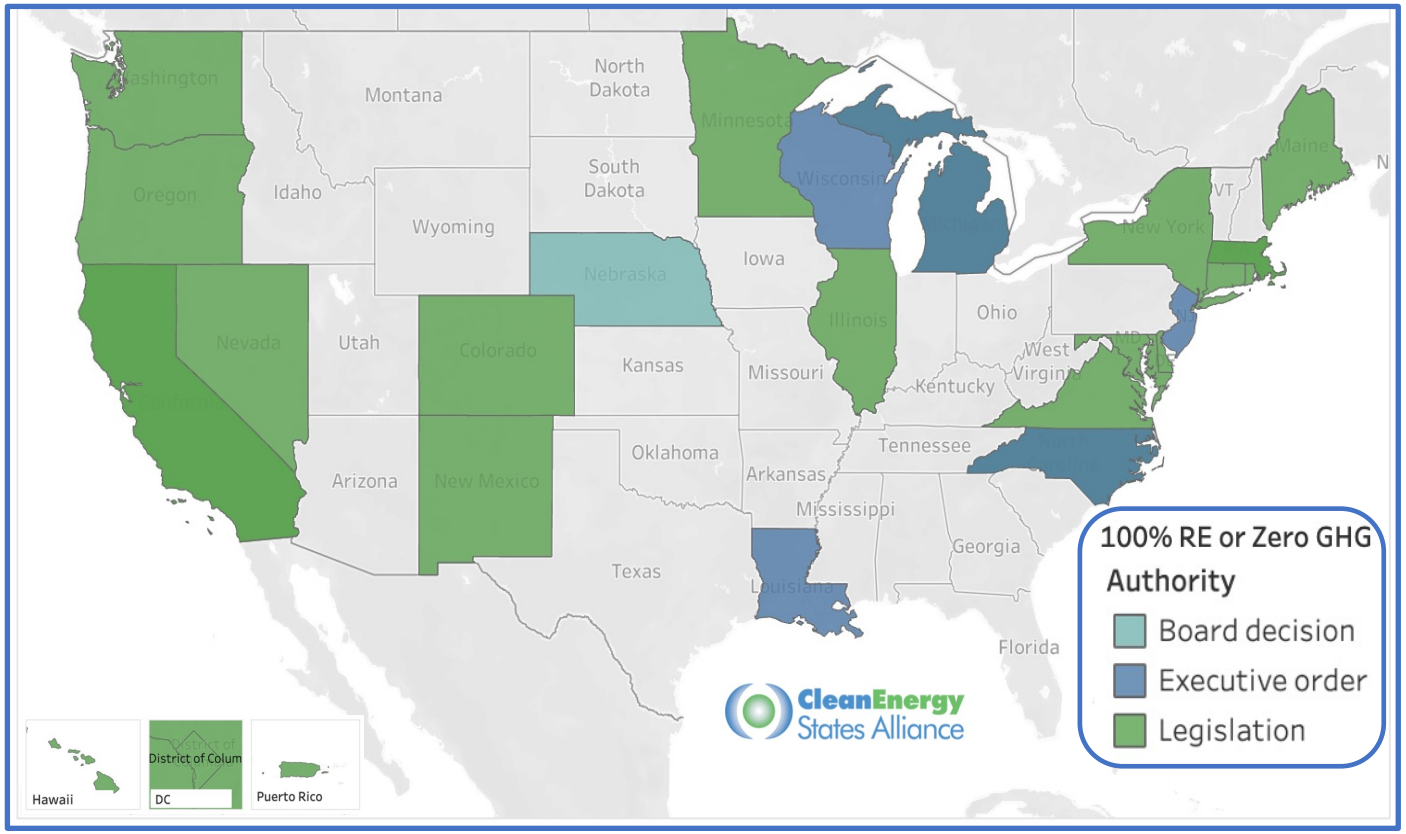
Hundreds died during the Texas winter storm power crisis in Feb 2021.



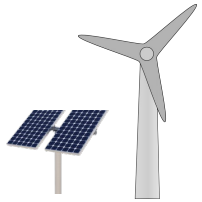
How do we plan electricity systems that dependably meet demand today?

Backup reserves of **dispatchable** fossil or **firm** nuclear generation.

By midcentury, many states and territories aim to dramatically increase wind and solar capacities.



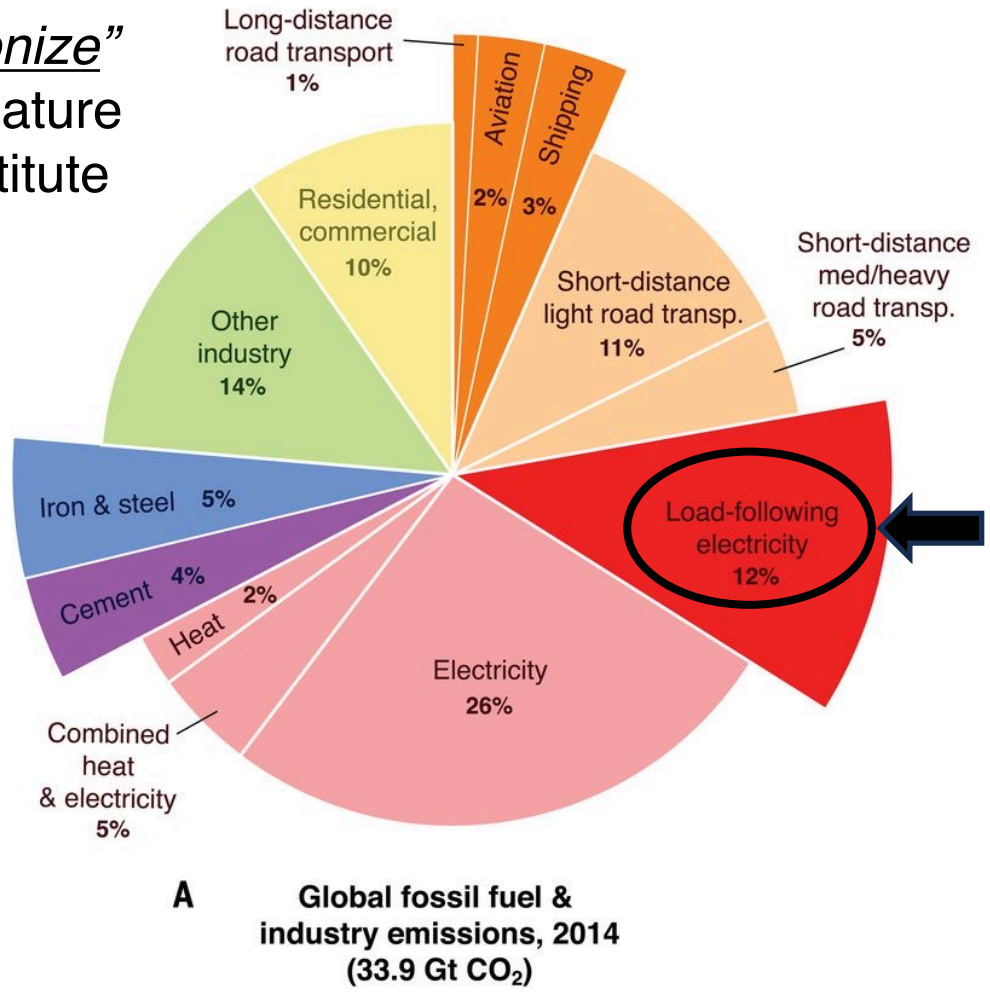
Within 100% carbon-free mandates, many states have **wind and solar capacity requirements**.



Transition from **dispatchable** to **variable** electricity

Load-following electricity is a difficult-to-decarbonize sector

"difficult-to decarbonize" sectors without a mature technological substitute



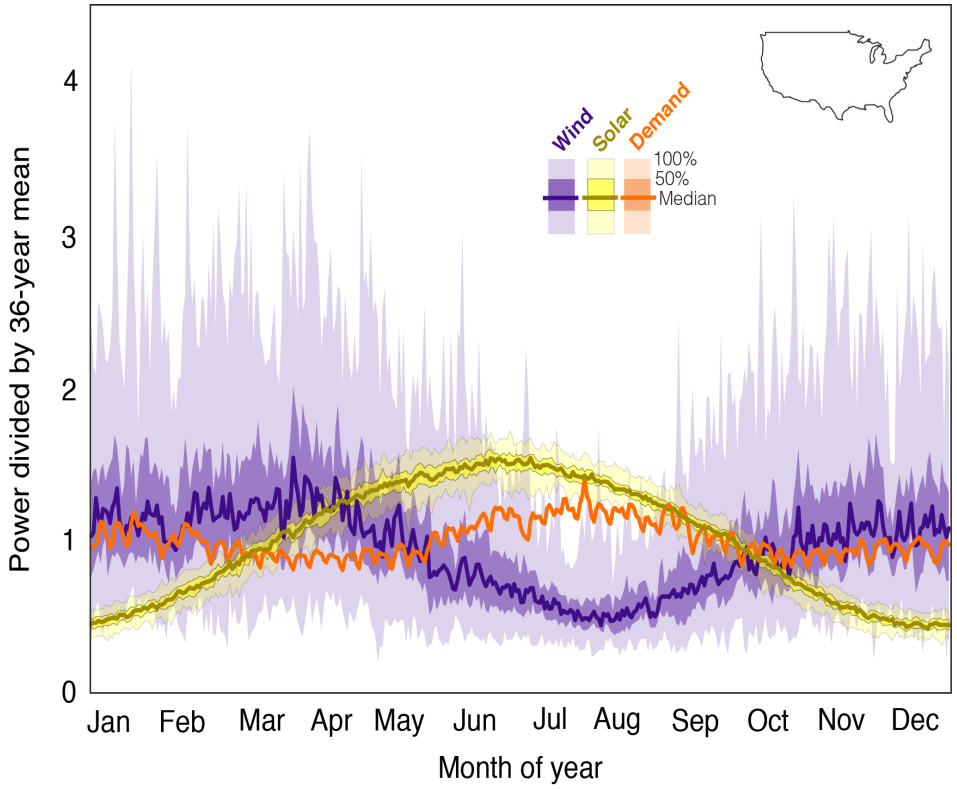
A **Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)**

Load-following electricity

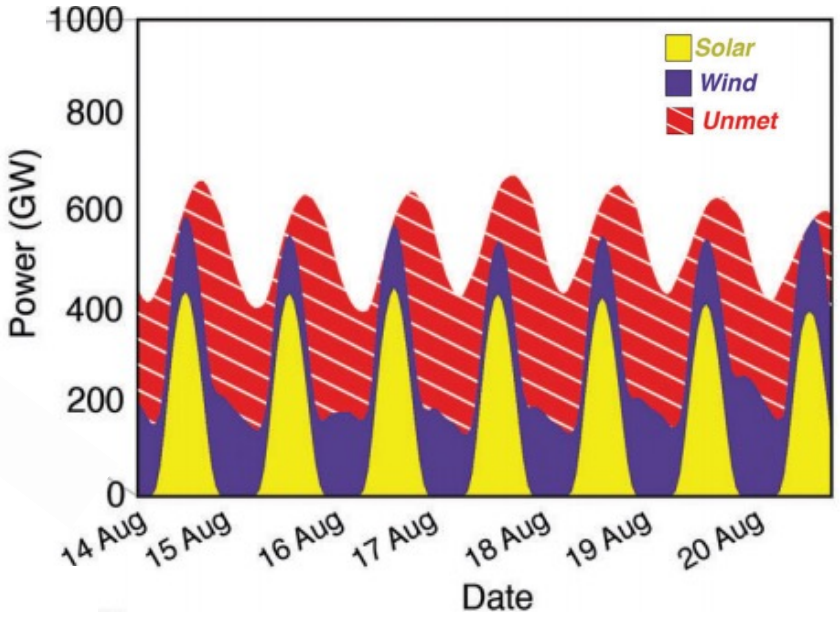
12% of global emissions

Davis et al., Net-Zero Emissions Energy Systems. *Science,* **2018**.

Wind and solar are variable and unreliable



Wind and solar resources **vary over daily, seasonal, and inter-annual timescales**



Reliability requirement for resource adequacy is that lost load shall not exceed **"one hour in a decade"**

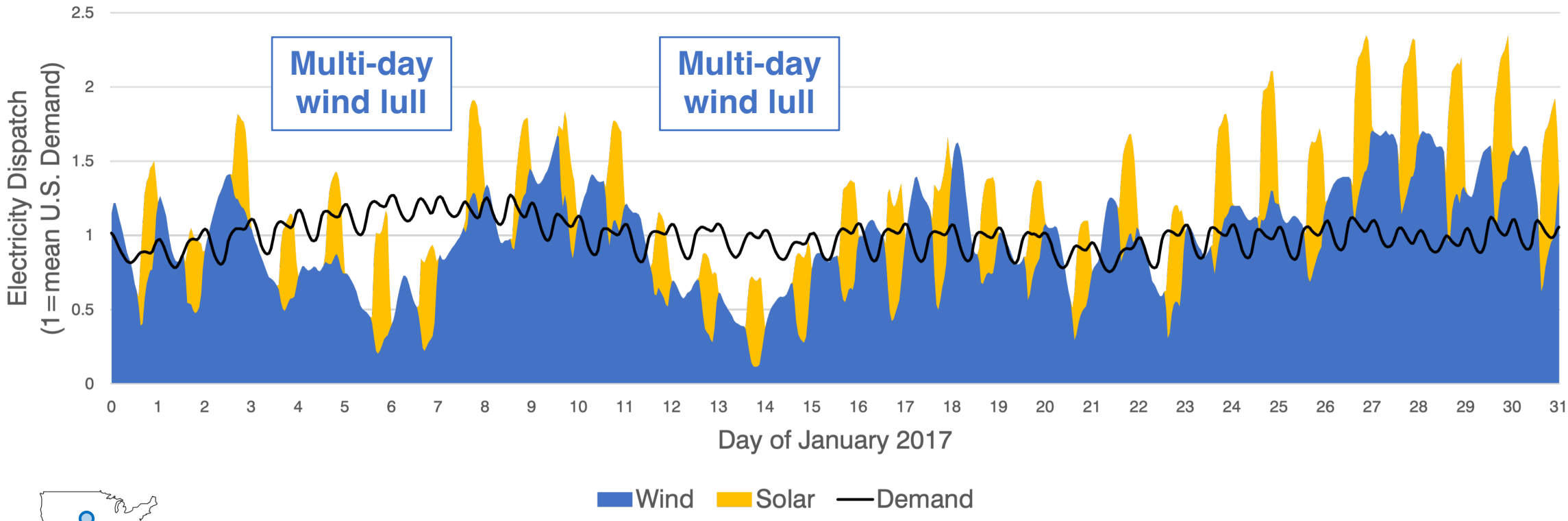
North American Electric Reliability Corporation

Shaner et al., Geophysical constraints on the reliability of solar and wind power in the United States. *EES*, **2018**.

Wind and solar constraints guide energy storage opportunities

Wind and solar constraints		Energy storage opportunity ★
Extreme weather years Ruggles, Virgüez, ..., Dowling et al., *APEN,* **2024**.	→	**Multi-year & seasonal storage functional roles** Dowling et al., *Joule,* **2020**.
Droughts and seasonal lulls Rinaldi, Dowling et al., *ES&T,* **2021**.	→	**Large volumes of low-cost energy storage** Li*, Virgüez*, Dowling* et al., *ES&T,* **2024**.
Curtailed (wasted) electricity Ruggles, Dowling et al., *APEN,* **2024**.	→	**Low-efficiency energy storage** Dowling et al., *EREN,* **2024**. Dowling et al., *ACS Appl Eng Mat.*, **2024.**

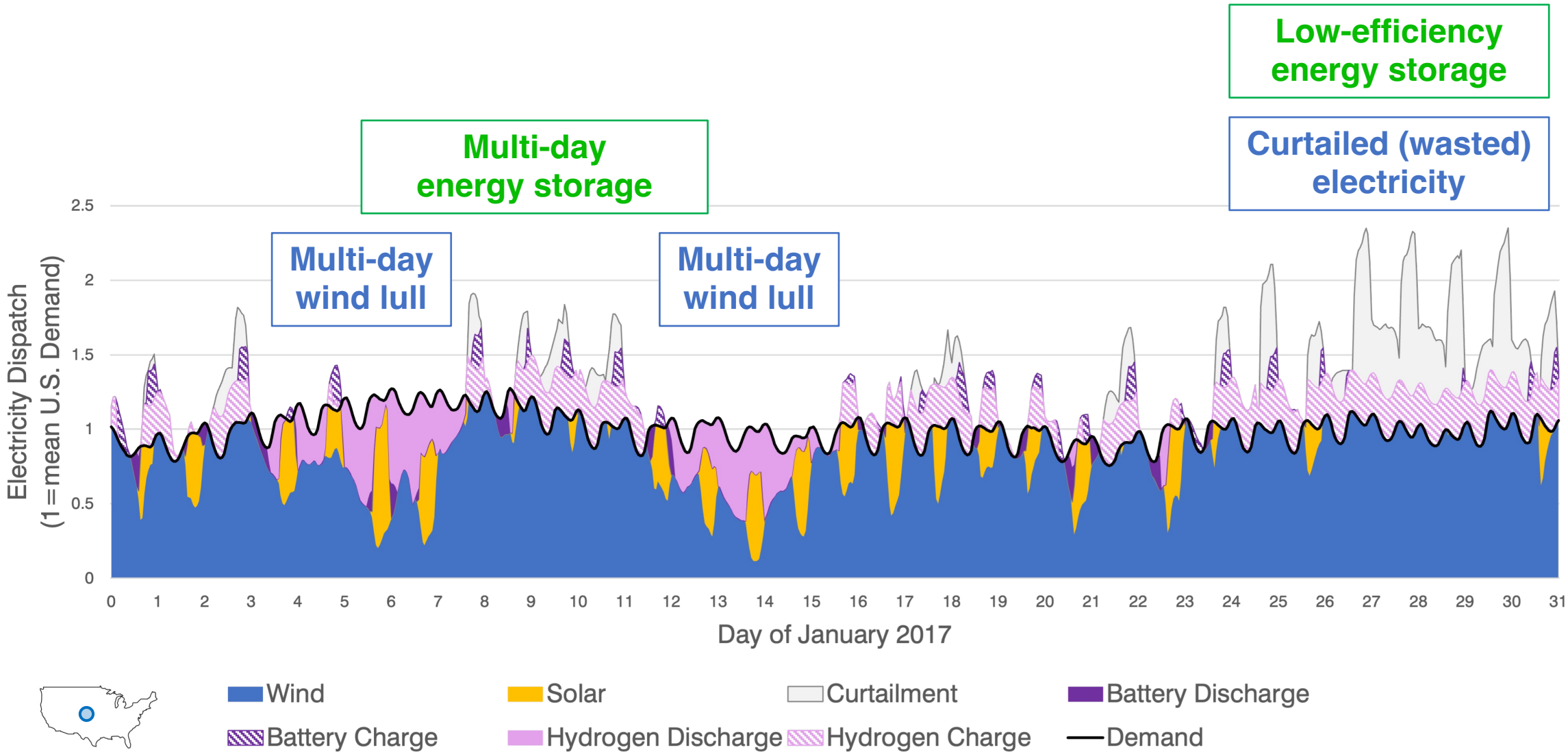
Wind and solar constraints guide energy storage opportunities



U.S. aggregated data with perfect transmission

Figure: J. Dowling

Wind and solar constraints guide energy storage opportunities

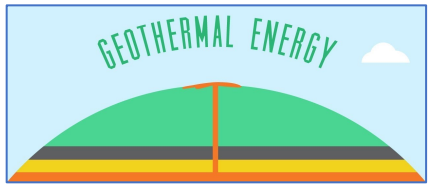


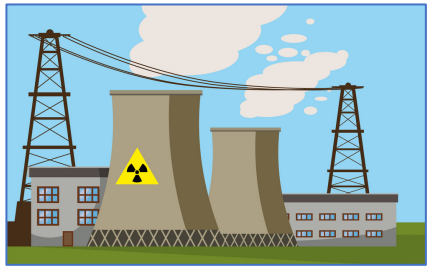
U.S. aggregated data with perfect transmission

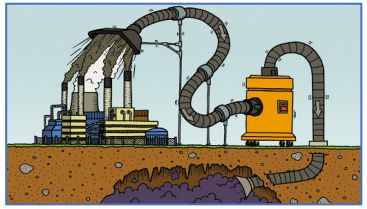
Figure: J. Dowling

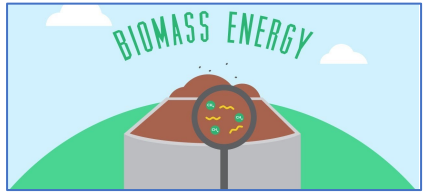
Various technology options may provide load-following electricity

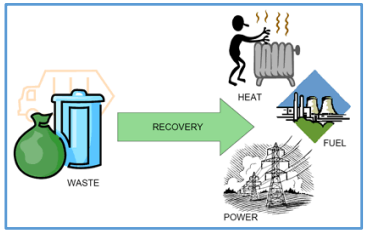
Clean firm power



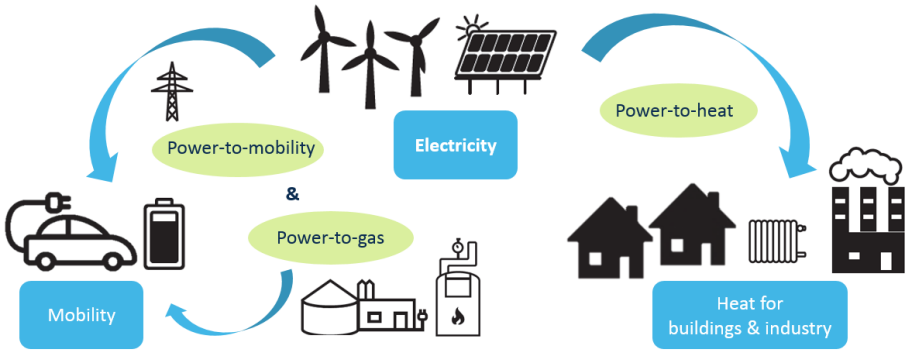




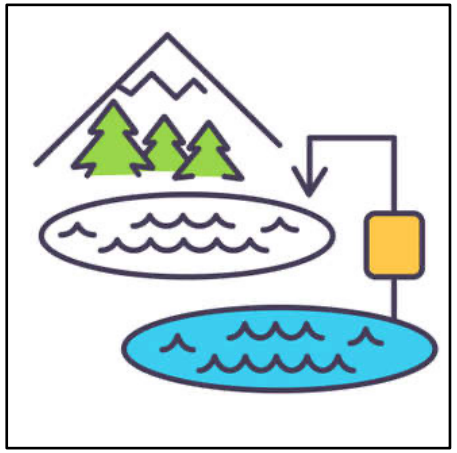


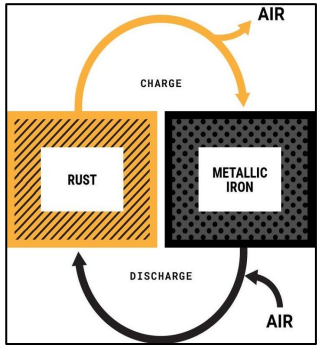


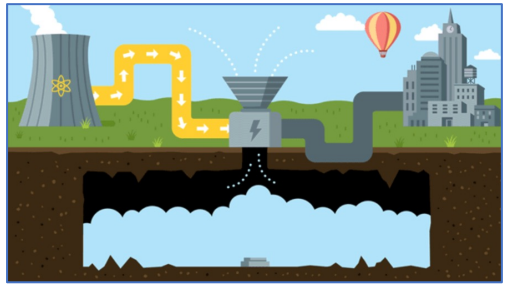
Sector coupling

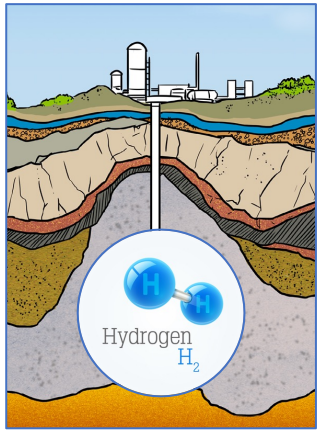


Long-duration energy storage ★









Dowling et al., Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule,* **2020**.

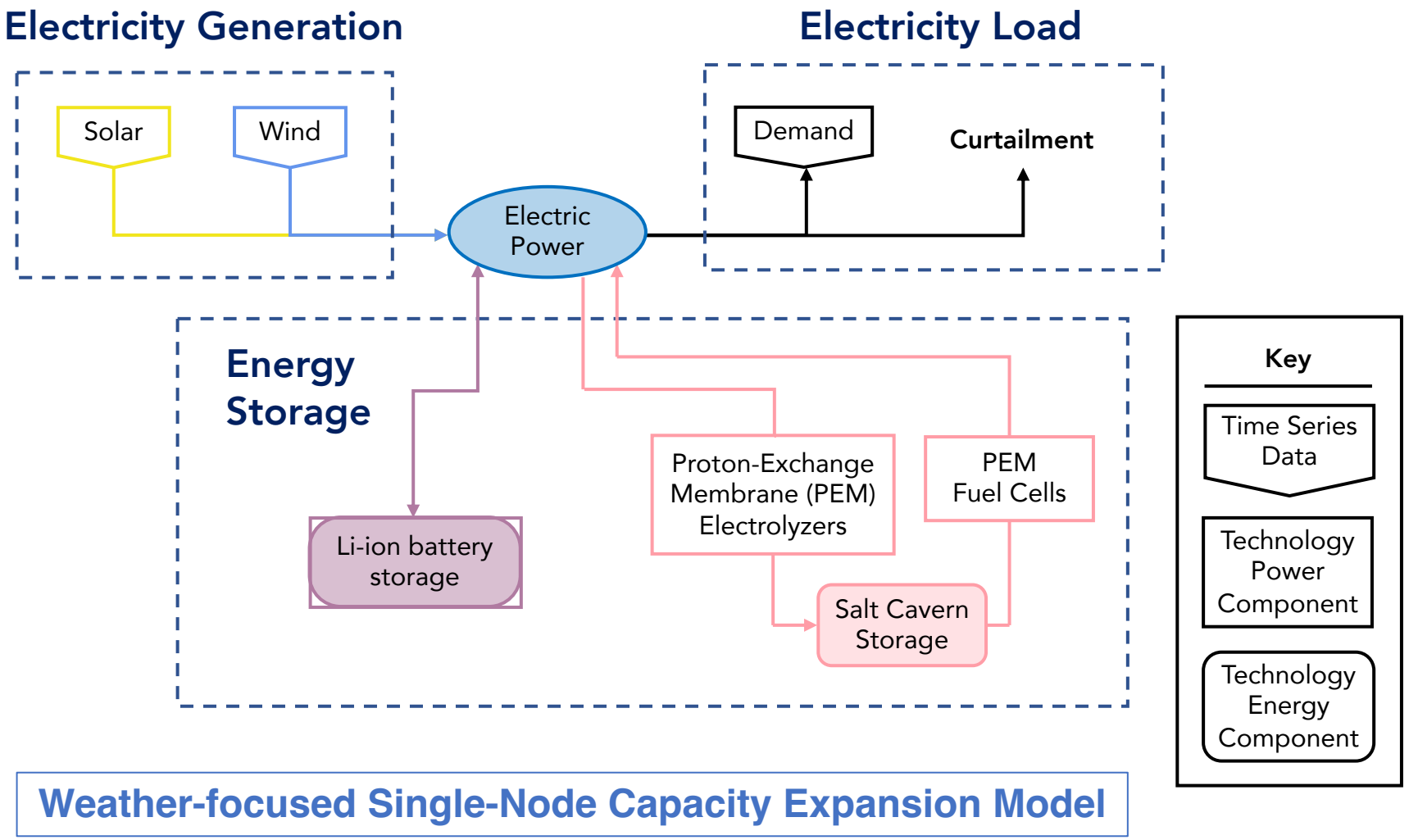
Primary Tool: Macro-Energy Model

Inputs:

- Current technology metrics and costs
- Historic wind, solar and demand data

Least-cost optimization:

- Constrains demand to be 100% satisfied at all hours only by wind, solar, and storage
- Objective function minimizes overall system cost
- Solve for capacity and hourly dispatch of each technology with perfect foresight



Weather-focused Single-Node Capacity Expansion Model

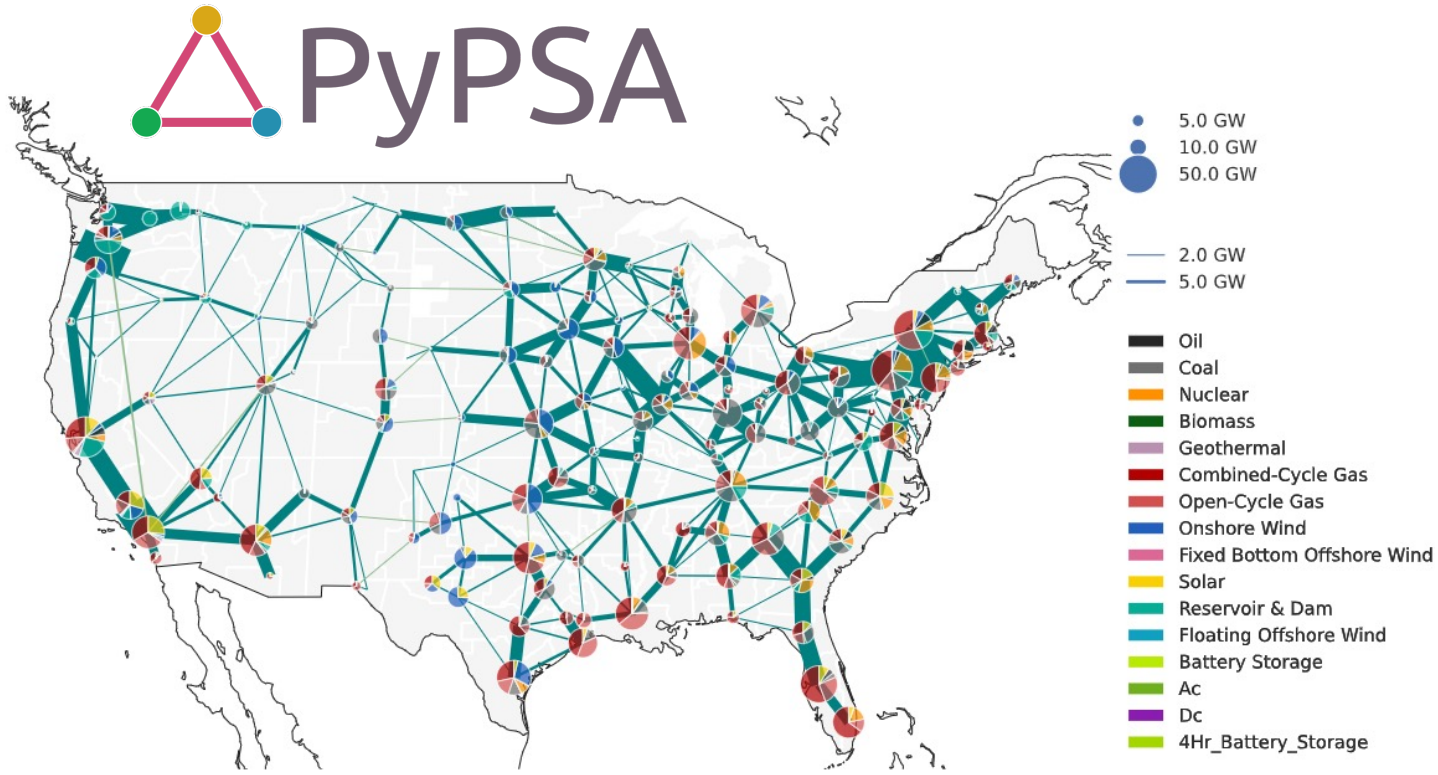
Hourly, **multi-decadal** weather data (Capacity factors, 1980-2017, MERRA-2)

Hourly, imputed demand data (EIA, 2015-2017)

GUROBI OPTIMIZATION

carnegie / MEM_public

Future work: Multi-nodal PyPSA-USA



For example: **What is the tradeoff between spatial and temporal resolution in capturing rare weather events like wind droughts?**

But for now, in this talk, we'll focus on the **value of including multi-decadal weather data** and show how sensitive the results are to it even in a single-node model.

GUROBI OPTIMIZATION

Macro Electricity Model (MEM)

Constraints

Capacity:

$$0 \leqslant C^{g,v,s} \qquad \forall g, v, s.$$

Dispatch:

$$\begin{aligned}
0 &\leqslant D_t^g \leqslant C^g f_t^g && \forall g, t. \\
0 &\leqslant D_t^v \leqslant C^v && \forall v, t. \\
0 &\leqslant D_t^{\text{to } s} \leqslant \tfrac{C^s}{\tau^s} && s = \text{battery}, \forall t. \\
0 &\leqslant D_t^{\text{from } s} \leqslant \tfrac{C^s}{\tau^s} && s = \textit{battery}, \forall t. \\
0 &\leqslant S_t^s \leqslant C^s && \forall s, t. \\
0 &\leqslant D_t^{\text{from } s} \leqslant S_t^s (1 - \delta^s) && \forall s, t.
\end{aligned}$$

Storage energy balance:

$$\begin{aligned}
S_1 &= (1 - \delta^s) S_T \Delta t + \eta^s D_T^{\text{to } s} \Delta t - D_T^{\text{from } s} \Delta t && \forall s\,. \\
S_{t+1} &= (1 - \delta^s) S_t \Delta t + \eta^s D_t^{\text{to } s} \Delta t - D_t^{\text{from } s} \Delta t && \forall s, t \in 1, \ldots, (T-1)\,.
\end{aligned}$$

System energy balance:

$$\sum_g D_t^g \Delta t + D_t^{\text{from } s} \Delta t = M_t + D_t^{\text{to } s} \Delta t \qquad \forall g, t.$$

Electricity sources = Electricity sinks

Dispatch of generation + Storage discharge = Demand + Storage charge

Macro Electricity Model (MEM)

Fixed costs for capacity

Variable costs for dispatch

Objective function

$$\text{minimize}\,(\text{system cost})$$

$$\text{system cost} =$$

$$\sum_g c^g_{\text{fixed}} C^g + \sum_g \left(\frac{\sum_t c^g_{\text{var}} D^g_t}{T} \right) + \sum_v c^v_{\text{fixed}} C^v +$$

$$\sum_s c^s_{\text{fixed}} C^s + \frac{\sum_t c^{\text{to } s}_{\text{var}} D^s_t}{T} + \frac{\sum_t c^{\text{from } s}_{\text{var}} D^s_t}{T}$$

Minimize system cost:

System cost = Fixed cost * (capacity) + variable cost * (dispatch)

Wind, solar, and storage have **fixed costs**, but **zero variable costs**.

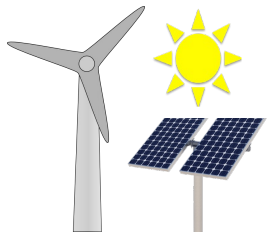
Natural gas has fixed costs (power plant) and variable costs (fuel).

Capacity cost (CapEx) and efficiency define energy storage in the model

Table 2. Base case costs and efficiencies. Assumptions from Hunter *et al* [7] unless otherwise noted.

	Power-to-H_2	H_2 storage	H_2-to-Power	Battery storage		Wind	Solar
Technology description	PEM electrolysis	Under-ground salt cavern	Stationary PEM fuel cell	Li-ion battery with coupled energy and power and a 4-hour charging time		Wind turbines, onshore	Solar PV, single-axis tracking
Technology type	Conversion	Storage	Conversion	Storage	Conversion	Generation	Generation
Capacity (fixed) cost type	Power capacity ($\$\,kW^{-1}$)	Energy capacity ($\$\,kWh^{-1}$)	Power capacity ($\$\,kW^{-1}$)	Energy capacity ($\$\,kWh^{-1}$)	Power capacity ($\$\,kW^{-1}$)	Power capacity ($\$\,kW^{-1}$)	Power capacity ($\$\,kW^{-1}$)
Capacity (fixed) cost	1706	2.0	1415	326	251	1436	1391
Project life (years)	30	30	30	30	30	30	30
Discount rate	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Capital recovery factor ($\%\,y^{-1}$)	8.06%	8.06%	8.06%	8.06%	8.06%	8.06%	8.06%
Fixed O&M cost ($\$\,kW\text{-}y^{-1}$, $\$\,kWh\text{-}y^{-1}$)	13	0.03	13	27	29	43	23
Efficiency	50%	—	70%	—		—	—
	36% round-trip efficiency			86% round-trip efficiency		—	—
Loss rate	—	$0.01\%\,y^{-1}$ (1.14×10^{-8} fraction h^{-1})	—	$12.1\%\,y^{-1}$ (1.38×10^{-5} fraction h^{-1})		—	—
Annualized capital costs paid hourly							
Fixed cost	$0.017\,\$\,kW^{-1}\,h^{-1}$	$0.00002\,\$\,kWh^{-1}\,h^{-1}$	$0.001\,\$\,kW^{-1}\,h^{-1}$	$0.004\,\$\,kWh^{-1}\,h^{-1}$		$0.018\,\$\,kW^{-1}\,h^{-1}$	$0.015\,\$\,kW^{-1}\,h^{-1}$
Variable cost	$0.000\,\$\,kW^{-1}\,h^{-1}$	$0.000\,\$\,kWh^{-1}\,h^{-1}$	$0.000\,\$\,kW^{-1}\,h^{-1}$	$0.000\,\$\,kWh^{-1}\,h^{-1}$		$0.000\,\$\,kW^{-1}\,h^{-1}$	$0.000\,\$\,kW^{-1}\,h^{-1}$

Geologic hydrogen storage is an example long-duration energy storage technology



Wind Solar

Power Conversion | **Energy Storage** | **Power Conversion**

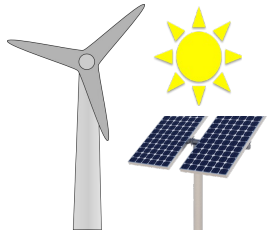
Battery

Low cost! **Charging**

Low cost! **Discharging**

Demand

86% efficient



Wind Solar

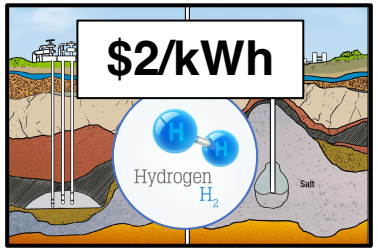
Hydrogen

High cost **Charging**

Electrolyzer

Low cost!

Geologic H_2 Storage



High cost **Discharging**

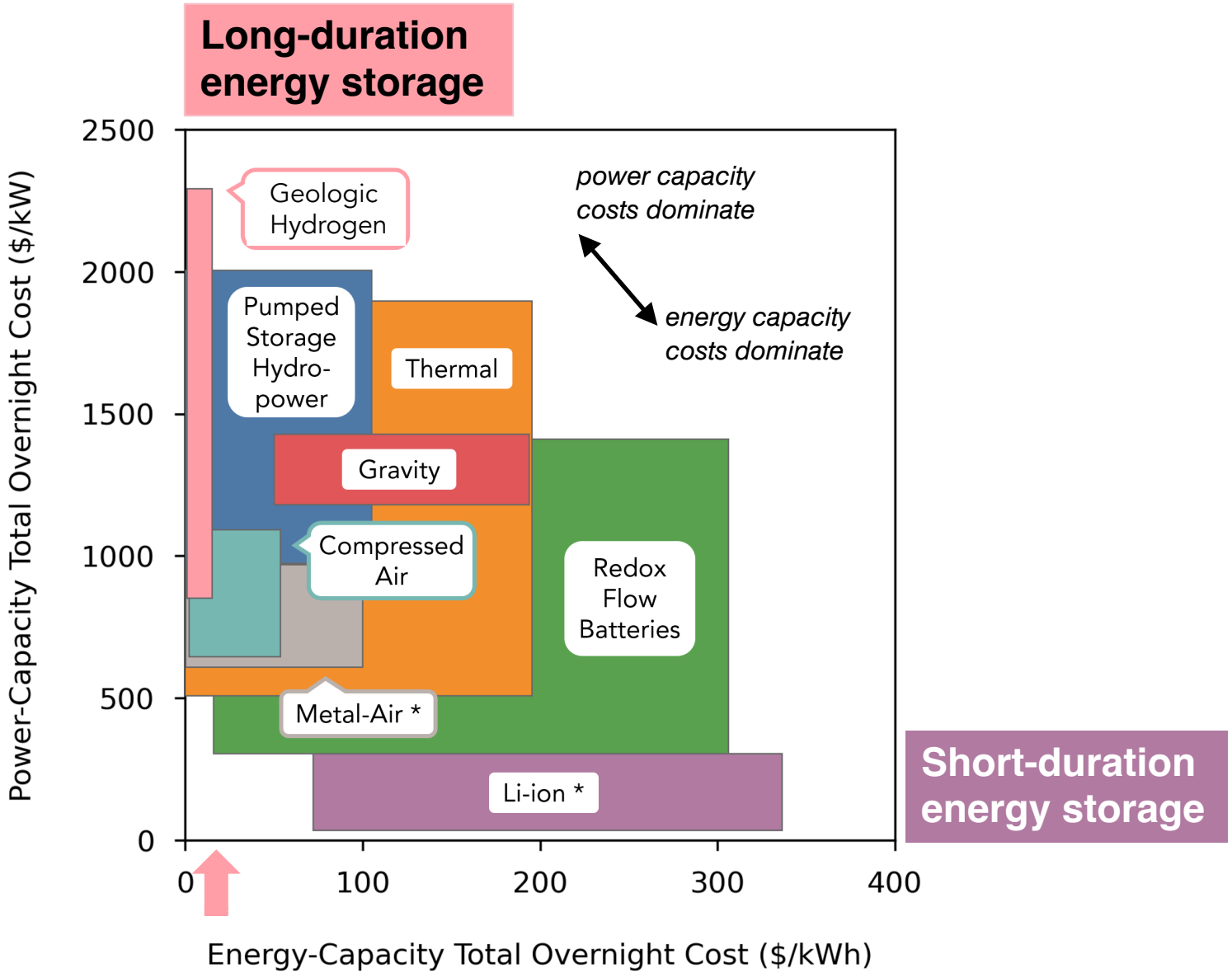
Fuel cell

Demand

36% efficient

Geologic hydrogen storage is an example long-duration energy storage technology

- Geologic hydrogen storage has the **lowest energy-capacity cost**.



Outline of Results

Long-Duration Energy Storage

- **Geologic Hydrogen Storage**
- **Energy Storage Portfolios**
- **Competition with Natural Gas**

At current technology costs, would long-duration energy storage reduce the cost of reliable wind-solar-battery systems?

Priors before doing this study

- We did not expect hydrogen energy storage to compete at current costs due to high charge/discharge costs and low efficiencies.

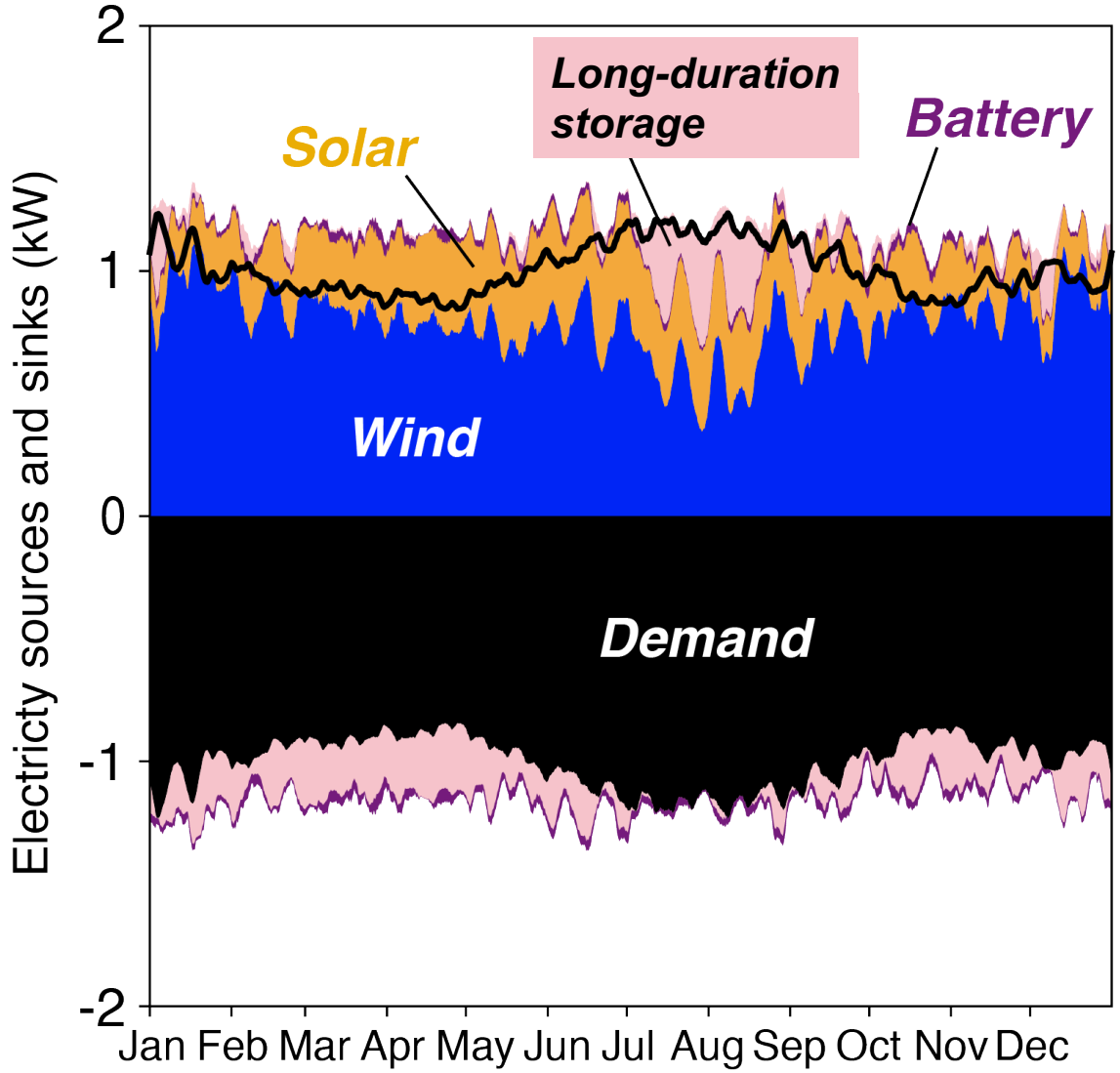
- Standard energy models typically used **1 year of weather data** and didn't capture seasonal or interannual variability

- California Energy Commission (CEC) definition of long-duration energy storage: > 10 hours

Dowling et al., Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule,* **2020**.

Long-duration storage fills seasonal storage needs at current technology costs

Macro-energy model least-cost optimization results:



- Low-cost energy storage, such as geologic hydrogen, can meet demand during **summertime lulls in wind power**.

Dowling et al., Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule,* **2020**.

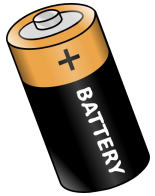
Seasonal and daily storage functional roles

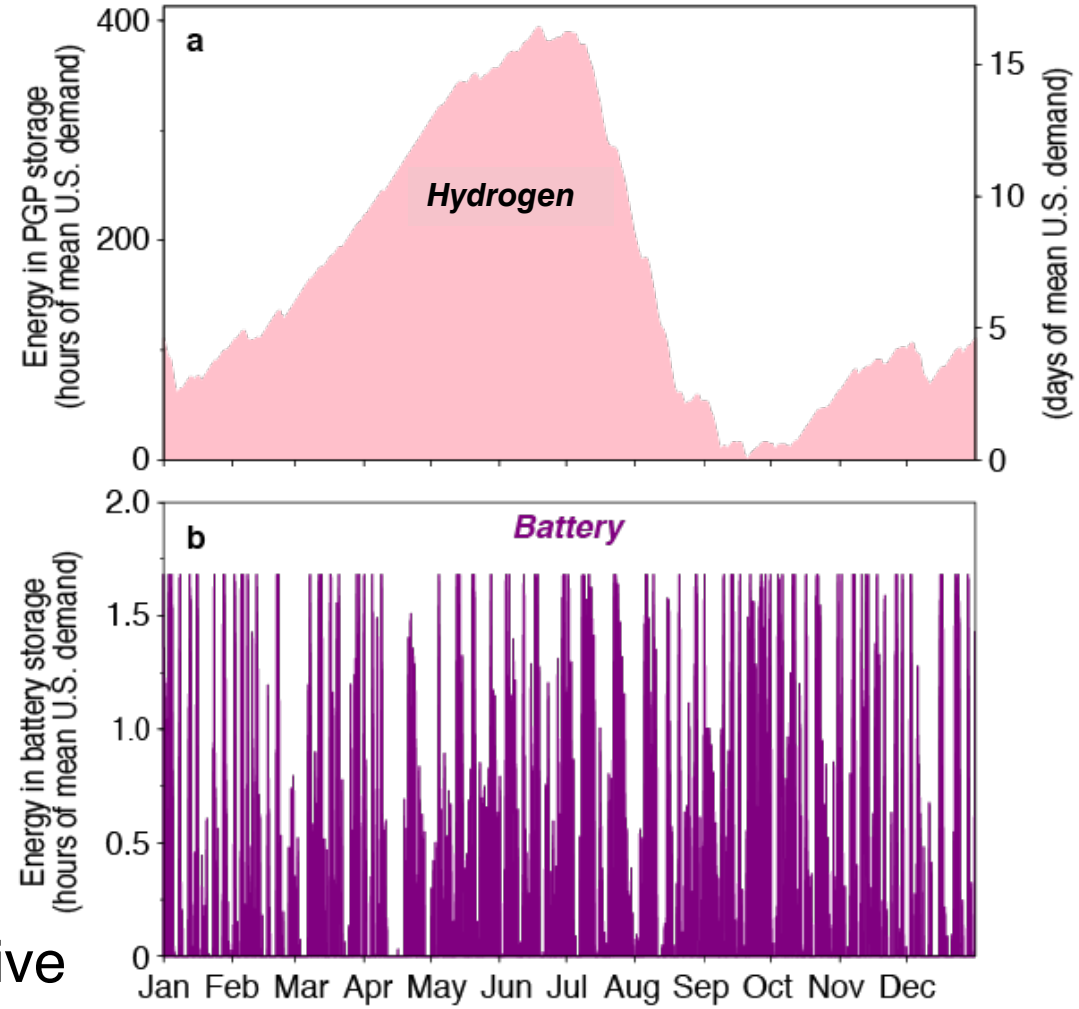
H_2 16 days

Inter-seasonal storage

Battery 1.7 hours

Intra-daily storage

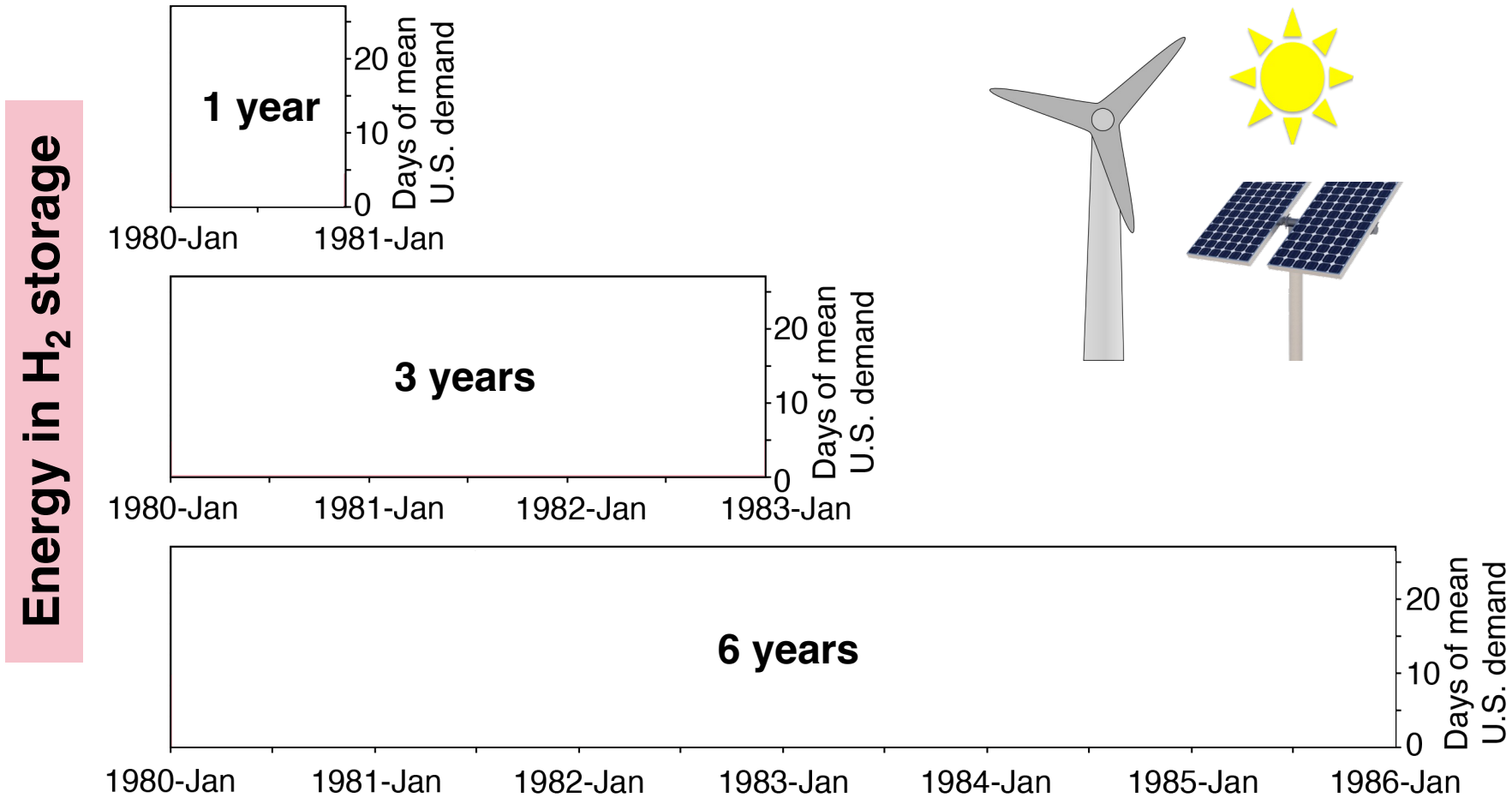




- Batteries are not cost-effective for seasonal energy storage.

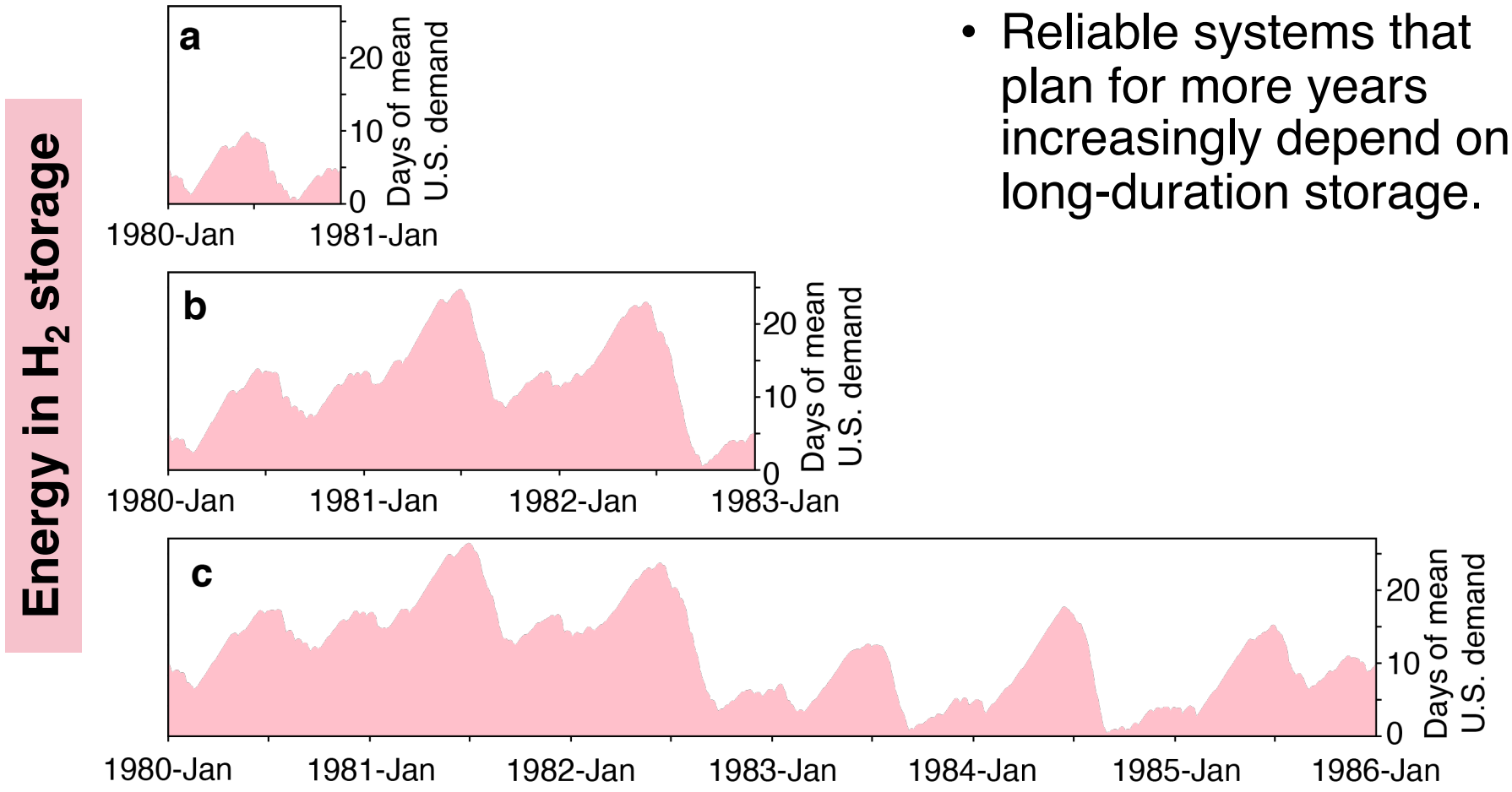
Dowling et al., Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule,* **2020**.

Long-term weather datasets, typically not used by utilities and regulators, capture the role and value of long-duration storage



Dowling et al., Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule,* **2020**.

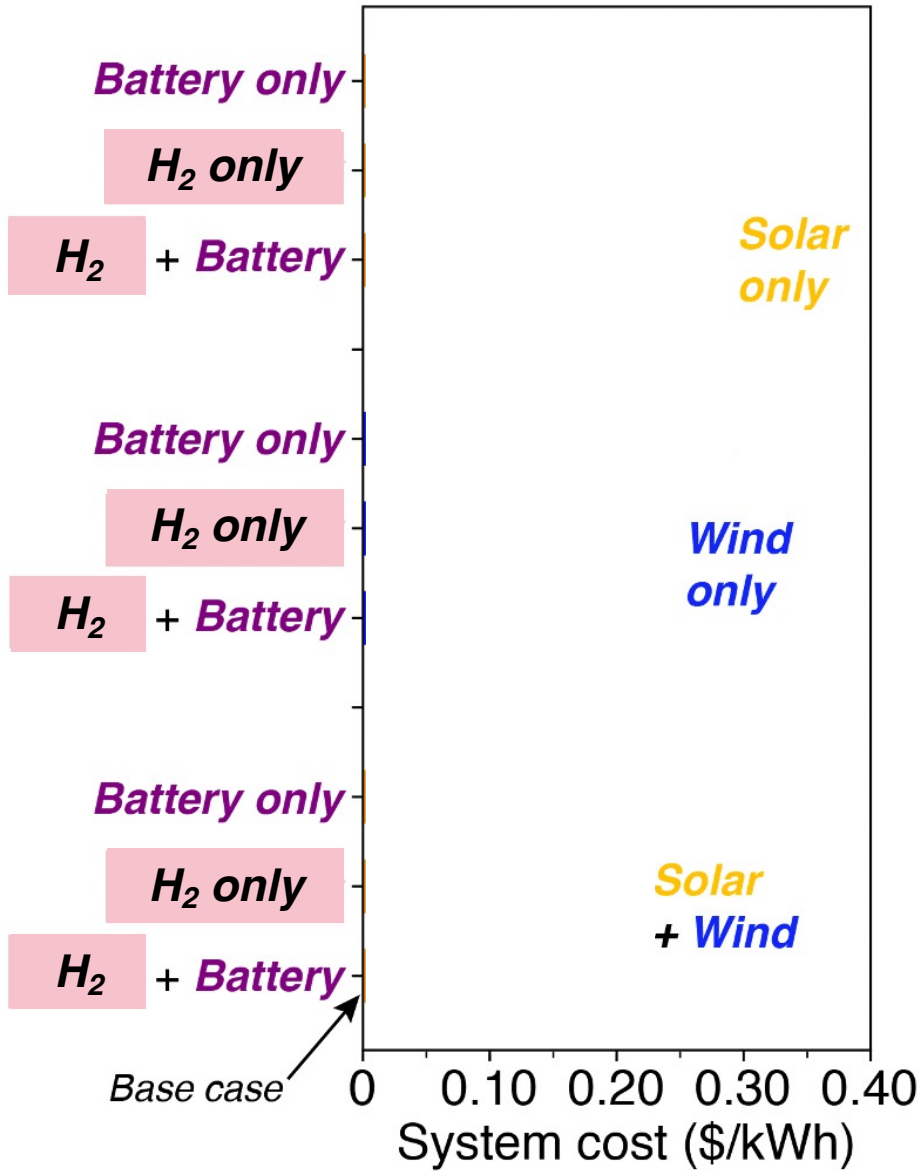
Multi-year hydrogen energy storage is cost-effective



- Reliable systems that plan for more years increasingly depend on long-duration storage.

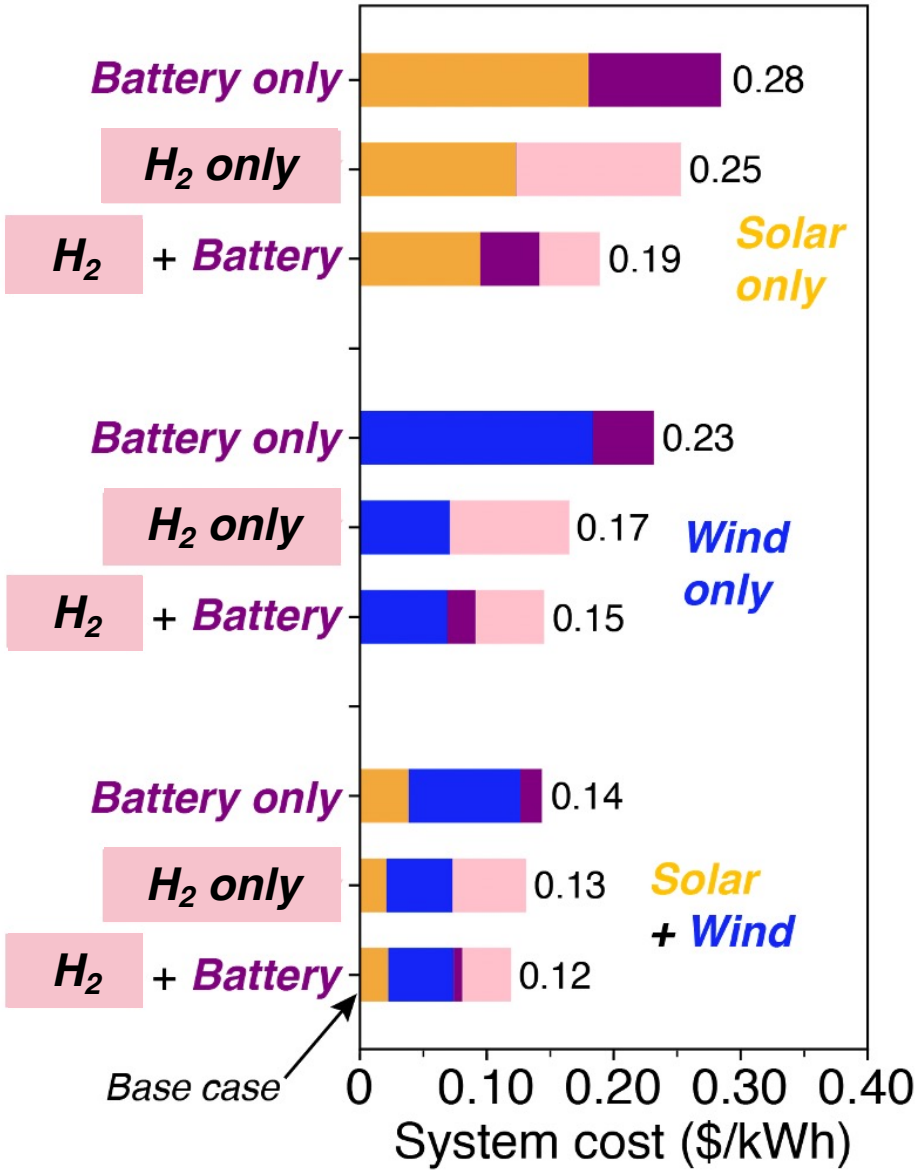
Dowling et al., Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule,* **2020**.

Add hydrogen energy storage at current technology costs:



Dowling et al., Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule,* **2020**.

Addition of hydrogen reduces costs in all cases considered



Dowling et al., Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule,* **2020**.

Key research advance

- **At current technology costs**, long-duration energy storage reduces the cost of reliable wind-solar-battery systems by **filling seasonal and multi-year storage functional roles**.

Wind and solar constraints guide energy storage opportunities.

Data integration methods advance:
Used multi-decadal weather data
Modeled an emerging technology

Google Scholar
Cited > 400

PLUMX
23 Policy Citations

Dowling et al., Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule,* **2020**.

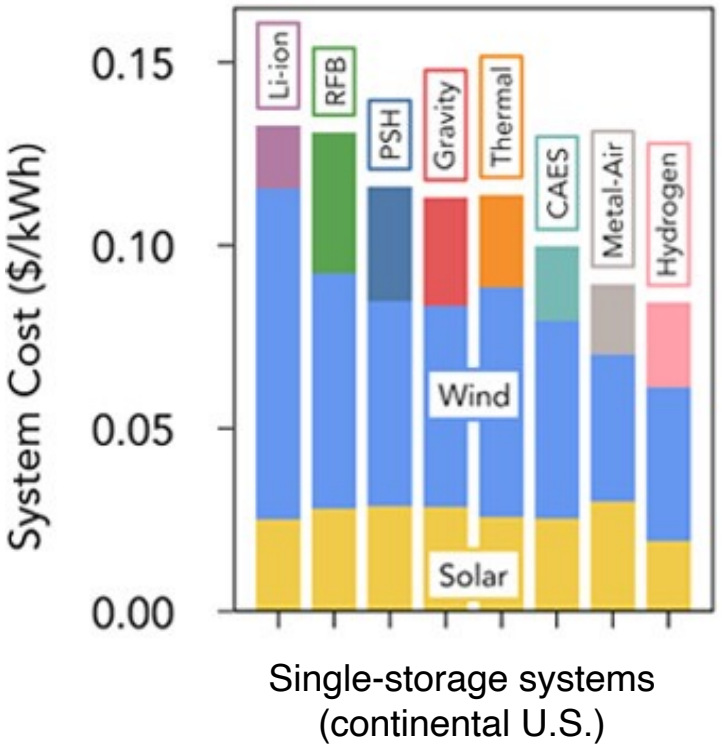
Outline

Long-Duration Energy Storage

- Geologic Hydrogen Storage
- Energy Storage Portfolios
- Competition with Natural Gas

What is the value of including long-duration storage compared to other energy storage options?

Energy Storage Options

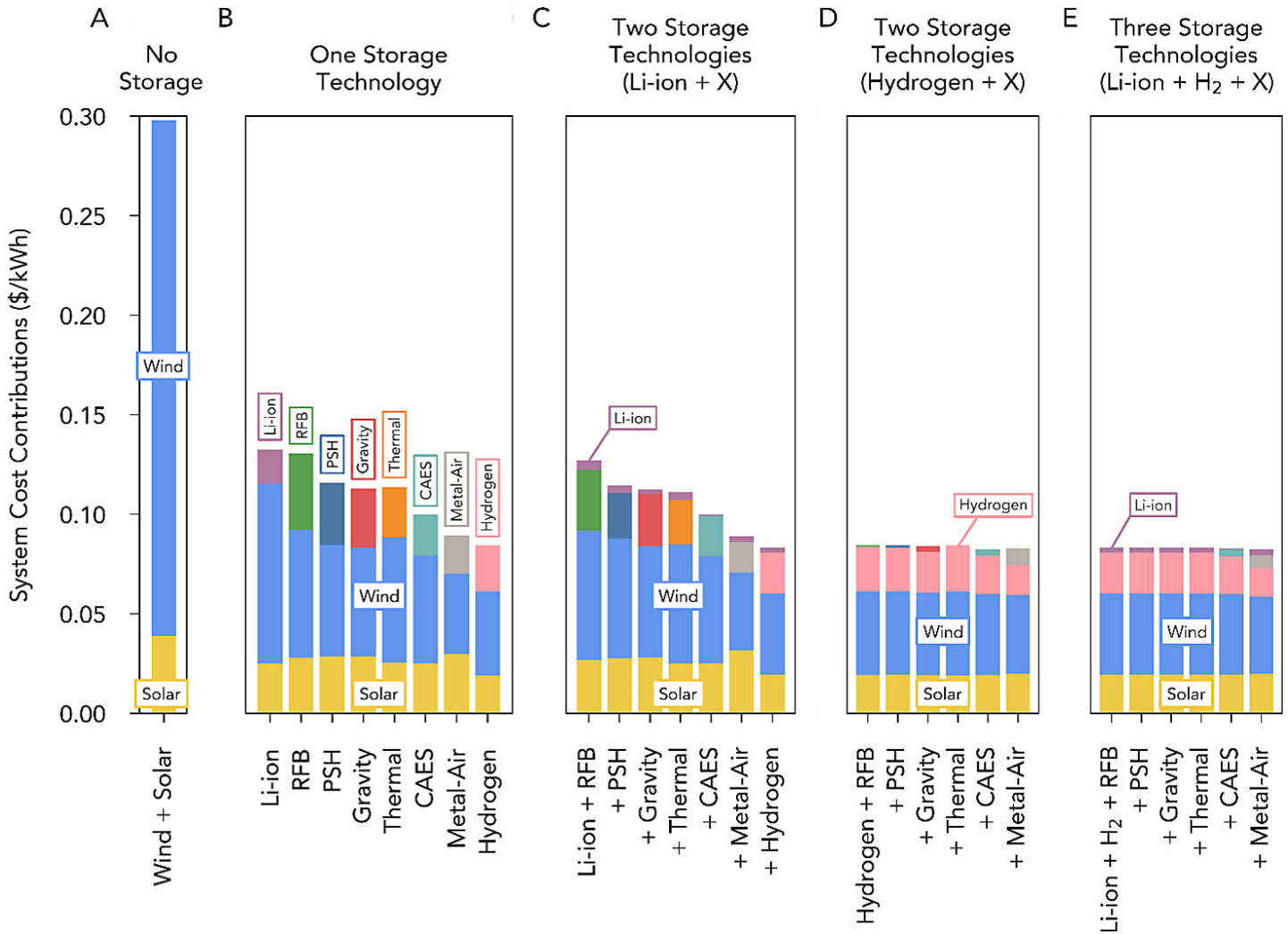


Geologic hydrogen storage and **metal-air batteries** were the most cost-effective energy storage technologies modeled due to their ***low energy capacity costs***.

- Hydrogen: **~2 $/kWh** energy-capacity cost
- Metal-air batteries: **~5 $/kWh** energy-capacity cost (20 $/kWh total cost with a fixed 100-h duration)

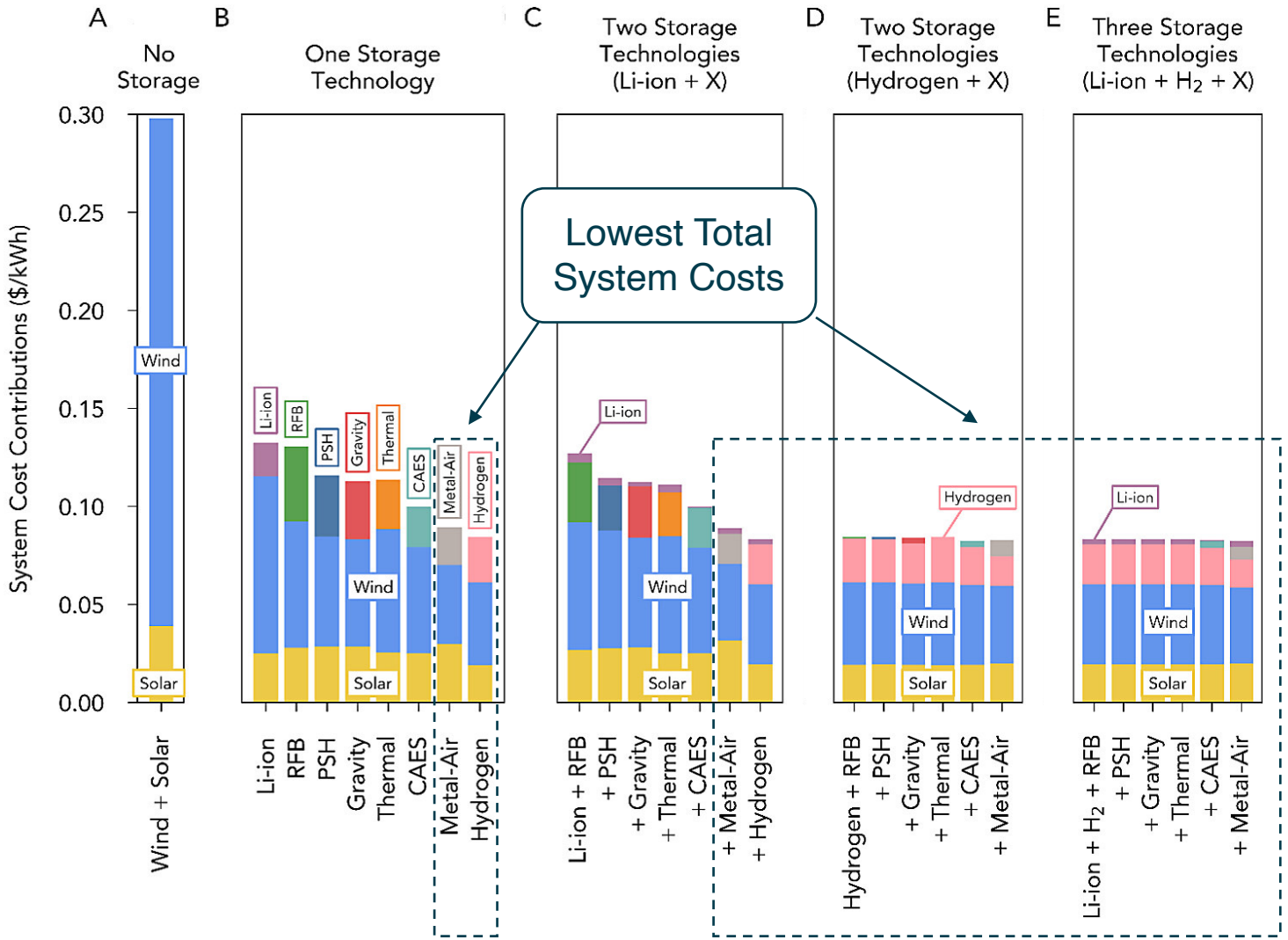
Li*, Virgüez*, Dowling* et al., *Environmental Science & Technology,* **2024**.

System costs of different energy storage portfolios (continental U.S.)

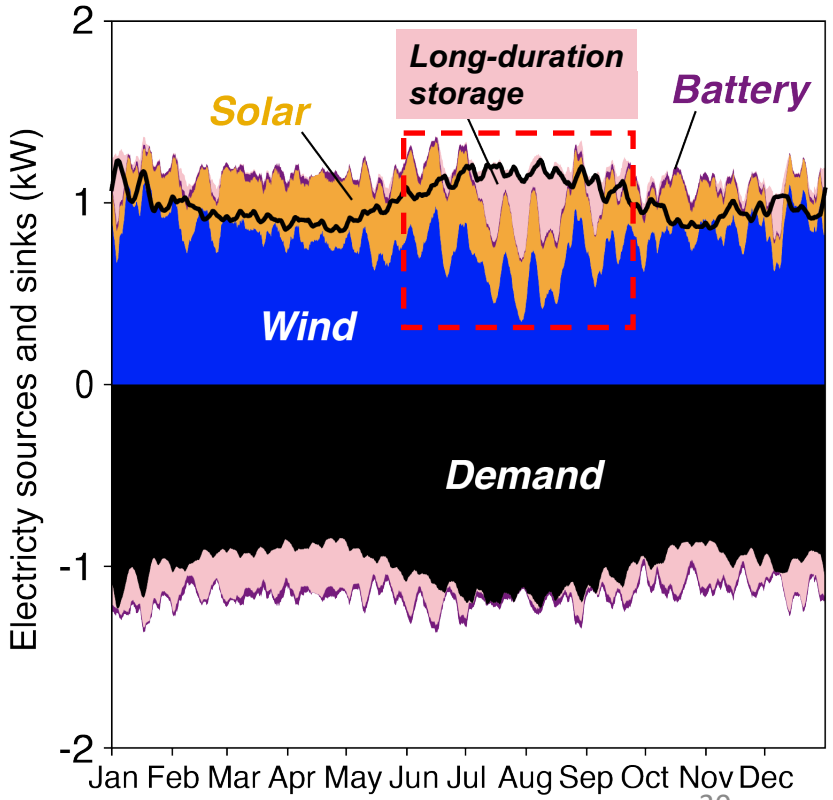


Li*, Virgüez*, Dowling* et al., *Environmental Science & Technology,* **2024**.

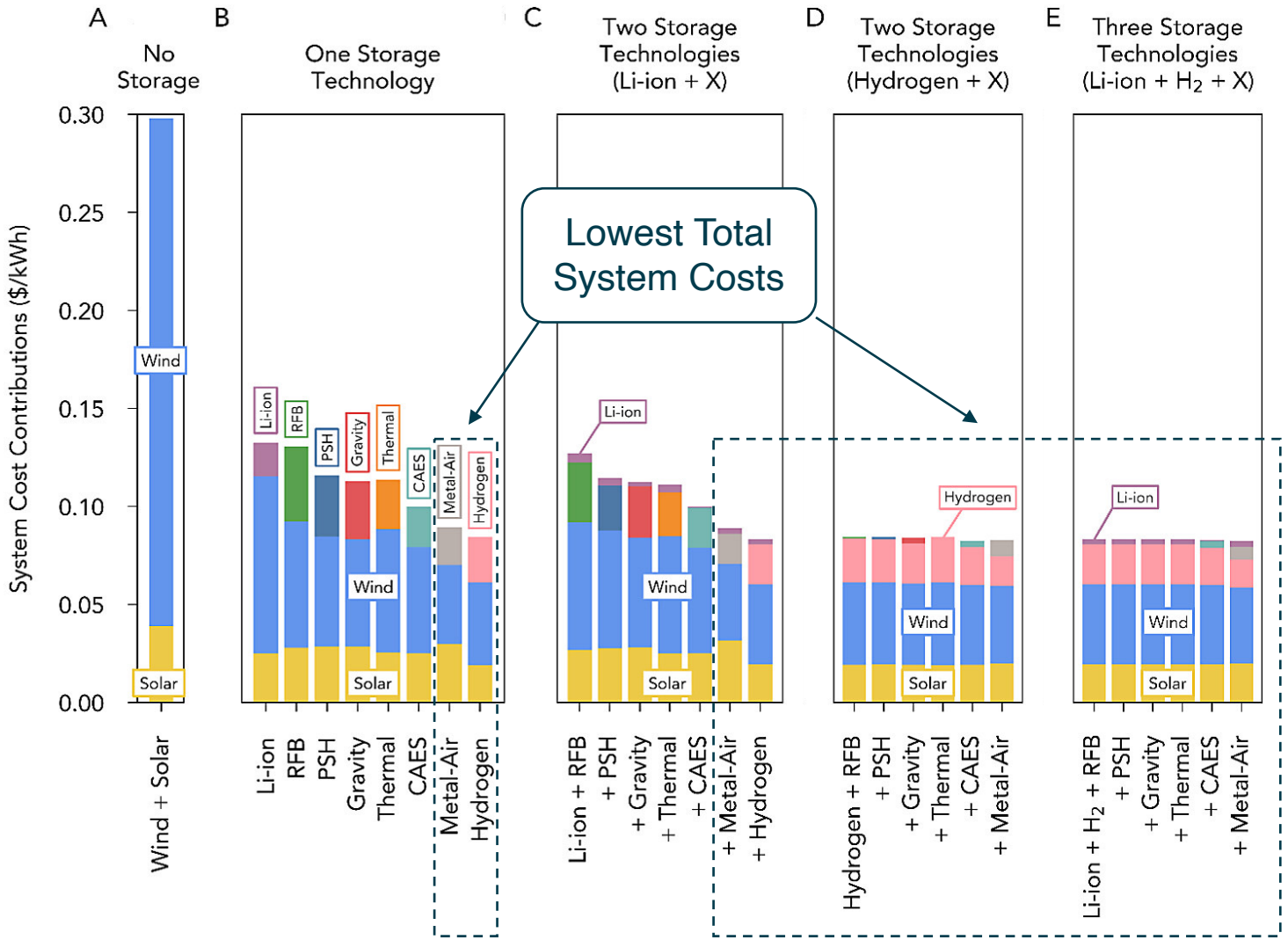
1. Deploying *underground hydrogen storage* or *metal-air batteries* led to the lowest total system costs



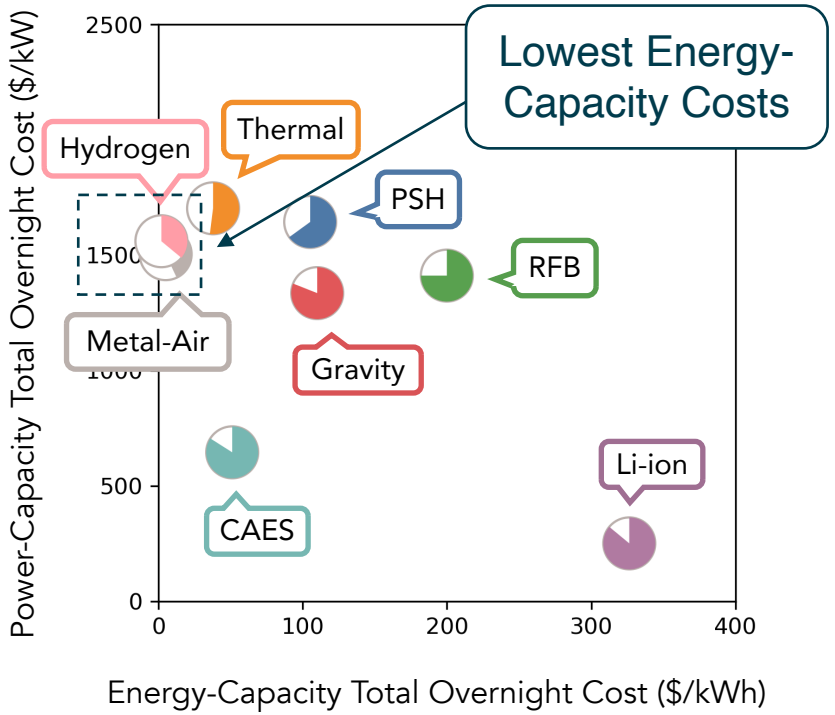
Long-duration storage **reduces wind-capacity overbuild** by meeting demand during summertime lulls in wind power.



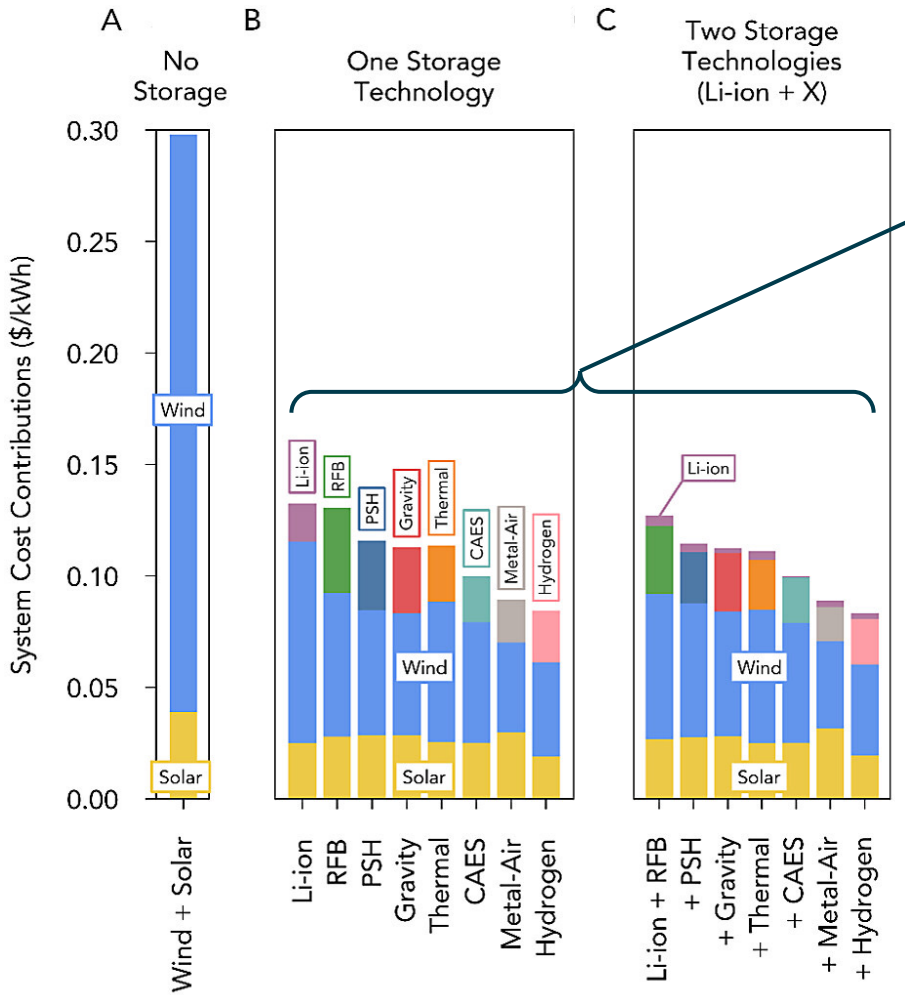
1. Deploying *underground hydrogen storage* or *metal-air batteries* led to the lowest total system costs



Metal-air batteries and geologic hydrogen storage have the **lowest energy-capacity costs** considered.

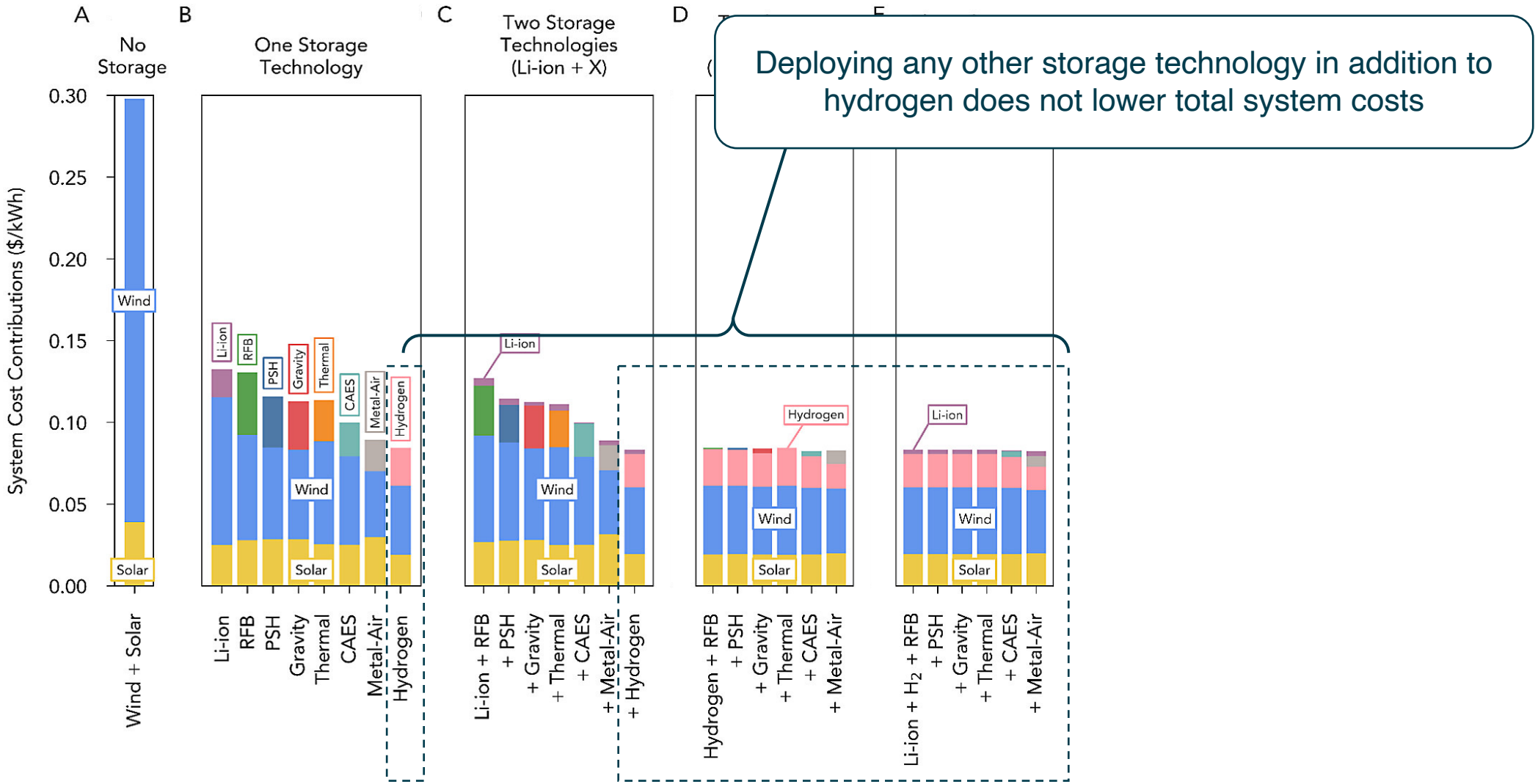


2. Long-duration storage may also cost-effectively provide short-term storage

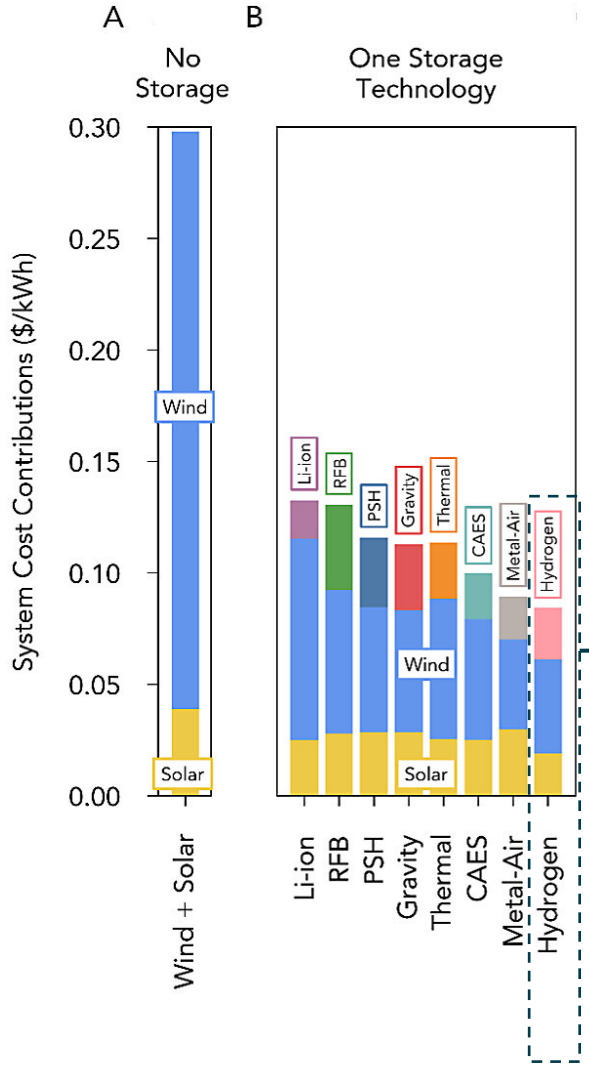


Deploying Li-ion batteries with a longer-duration storage technology does not substantially lower total system costs

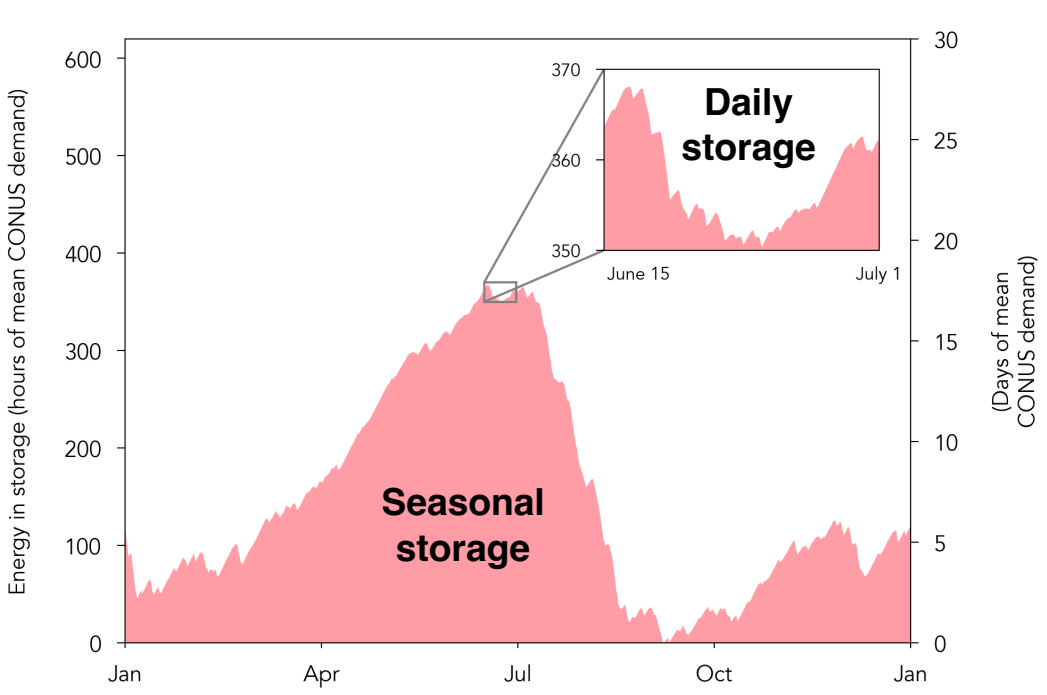
2. Long-duration storage may also cost-effectively provide short-term storage



2. Long-duration storage may also cost-effectively provide short-term storage



Least-cost systems contained sufficient power-capacity from long-duration storage to also meet short-term power needs.



Li*, Virgüez*, Dowling* et al., *Environmental Science & Technology,* **2024**.

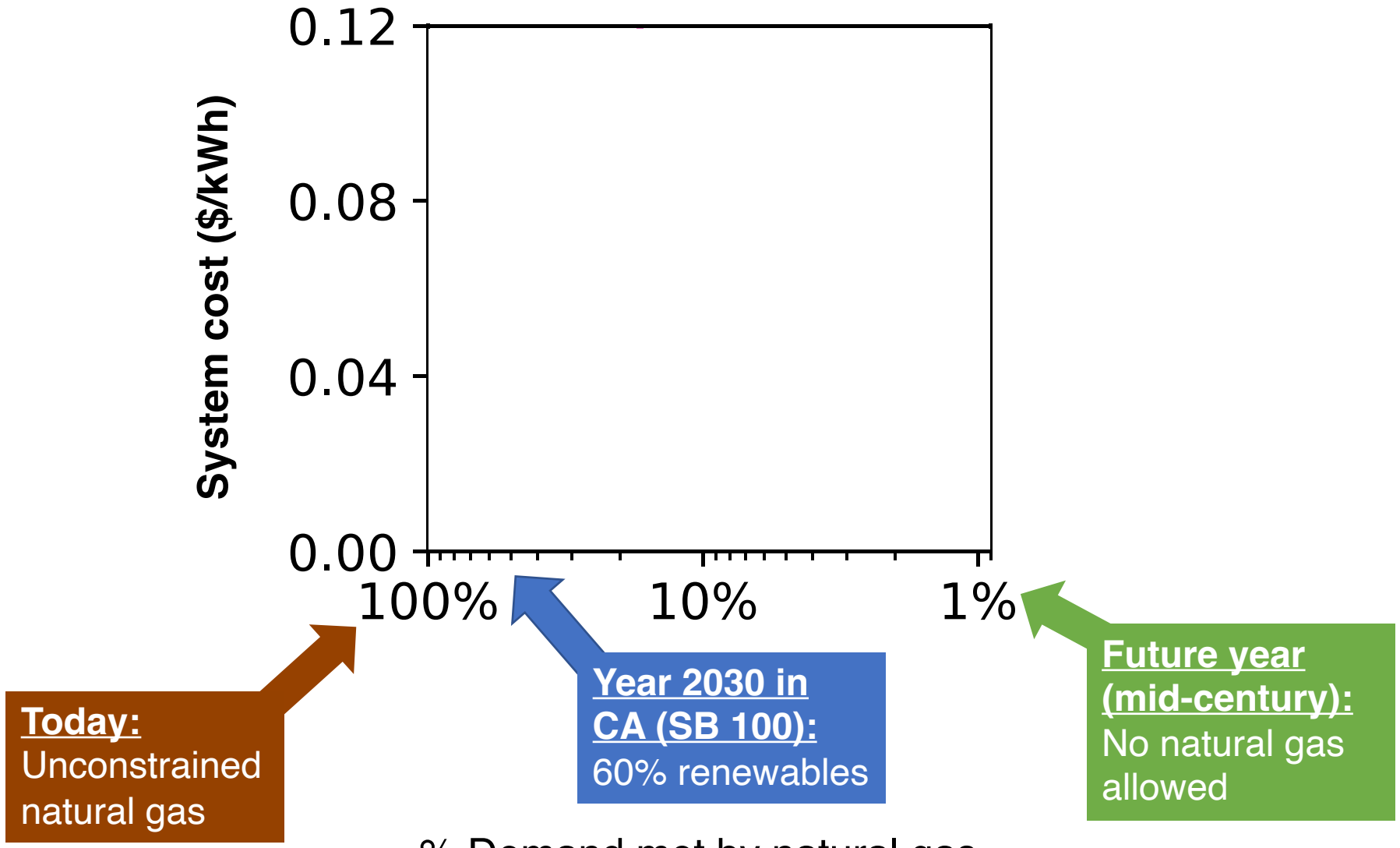
Outline

Long-Duration Energy Storage

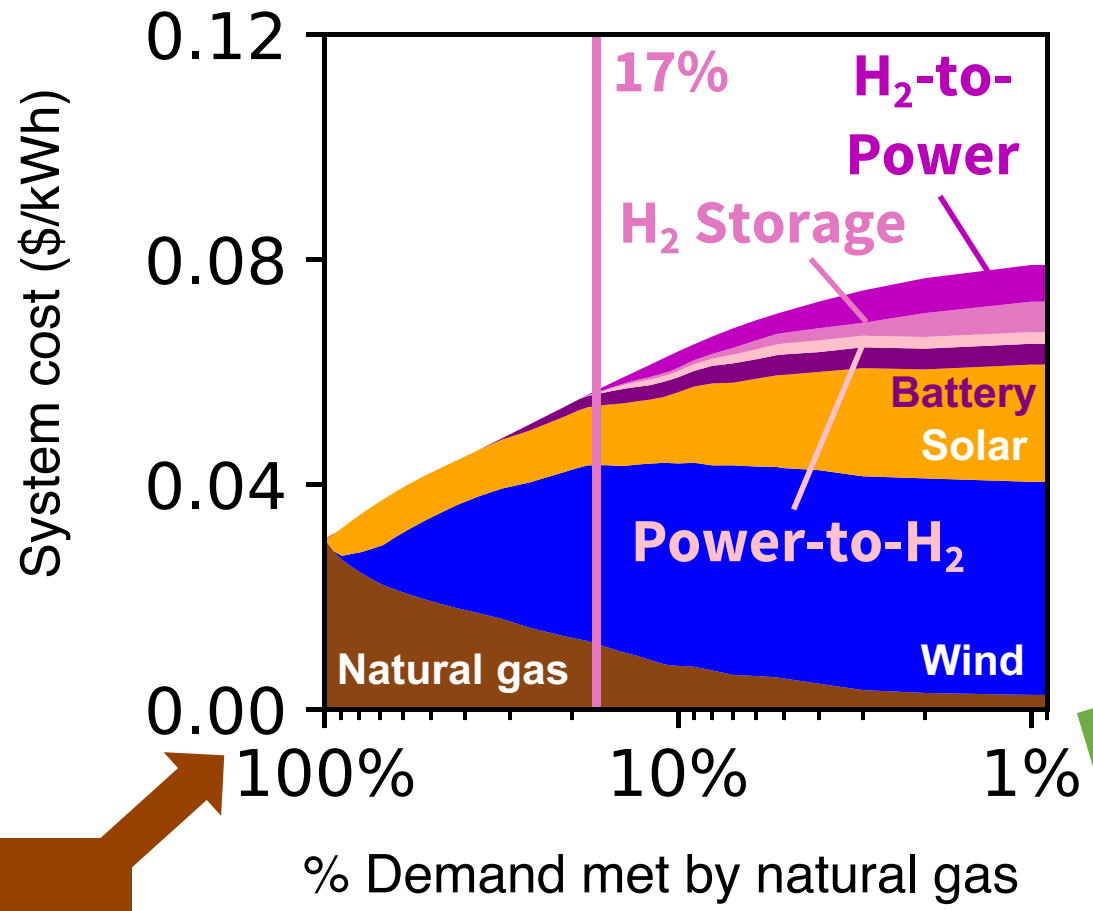
- Geologic Hydrogen Storage
- Energy Storage Portfolios
- Competition with Natural Gas

At what degree of decarbonization would hydrogen storage compete with natural gas?

At what degree of decarbonization do hydrogen storage technologies compete with natural gas?



Geologic hydrogen storage can reduce electricity costs in wind and solar systems with natural gas restricted to 17% of demand.



Today: Unconstrained natural gas

Future year (mid-century): No natural gas allowed

Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

Range of technology options

Lower cost options:

Base case:

Higher cost options:

Power Conversion

Power-to-H_2

Charging

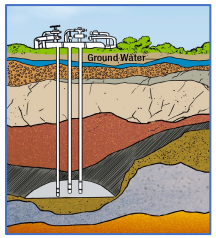
PEM electrolyzer

Energy Storage

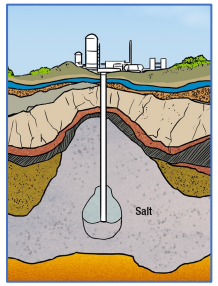
H_2 Storage

Depleted reservoir

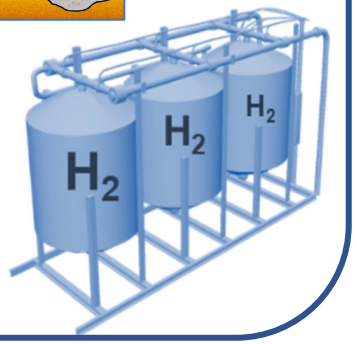
Low cost!



Salt cavern



Above-ground tank



High cost

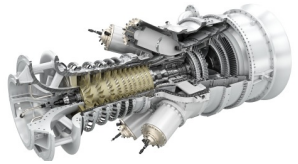
Power Conversion

H_2-to-Power

Discharging

H_2 combustion turbine

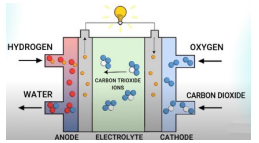
Low cost!



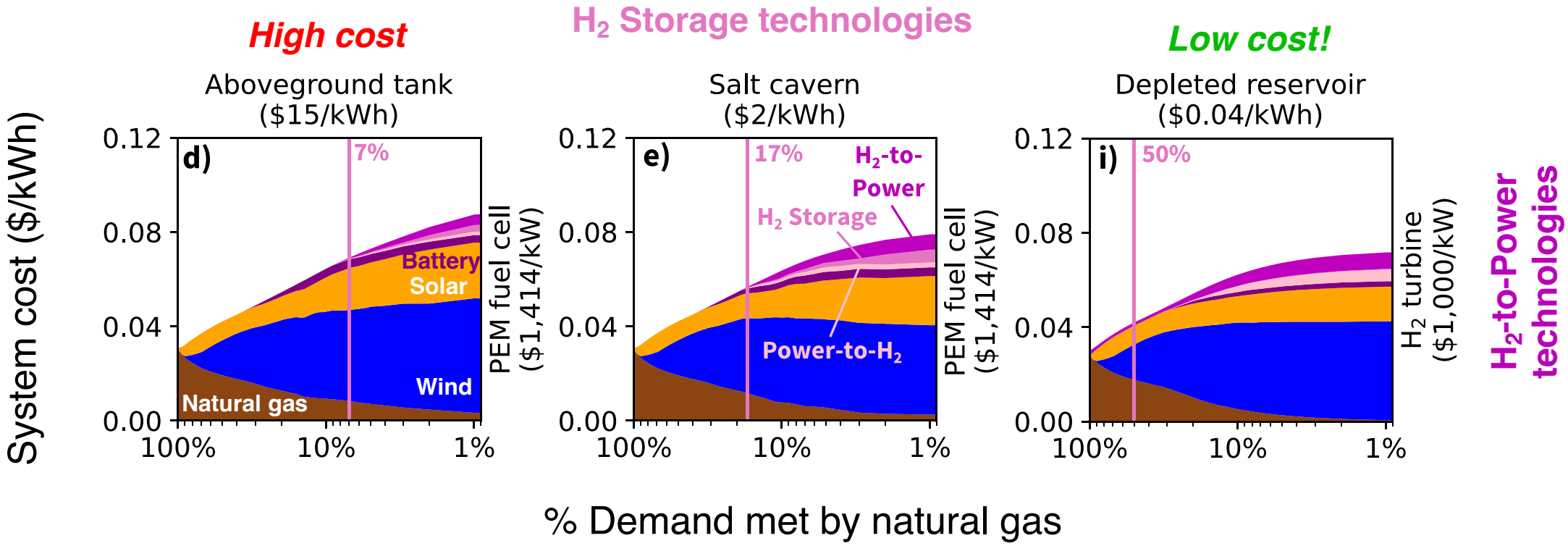
PEM fuel cell

Molten carbonate fuel cell

High cost



Geologic hydrogen storage is much more competitive with natural gas than aboveground tank storage



Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

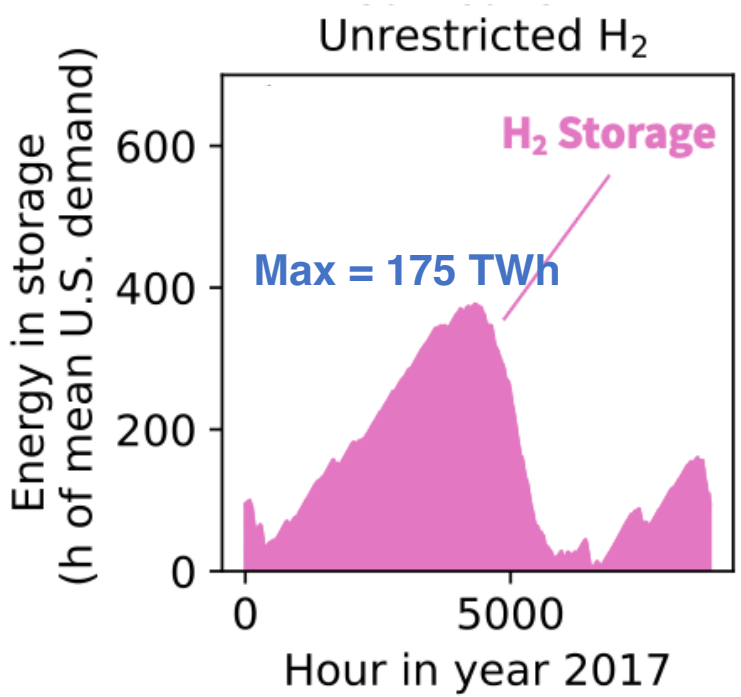
Outline

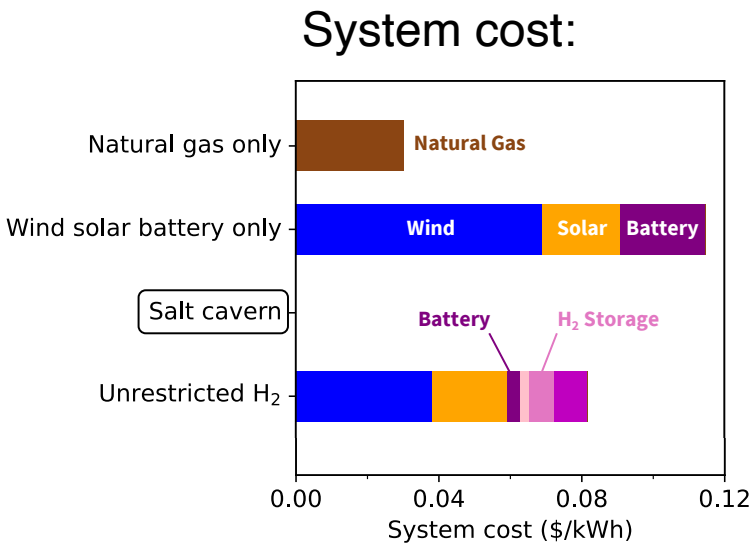
What capacity limits are there to geologic hydrogen energy storage?

Constraints and Innovation

- **Underground Storage Constraints**
- **High- and Low-Value Innovation**
- **Shift in Materials Chemistry Focus**

How much hydrogen energy storage might we want?

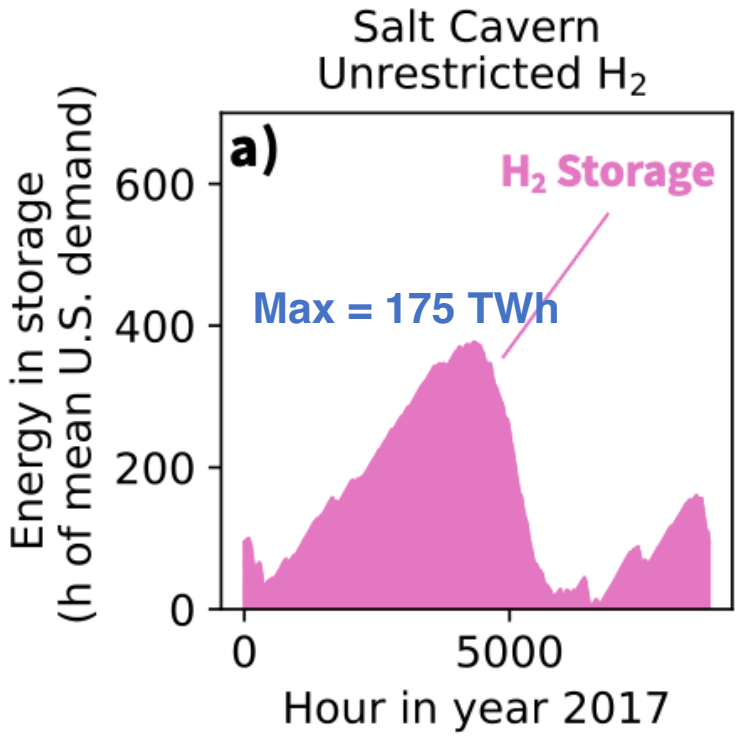


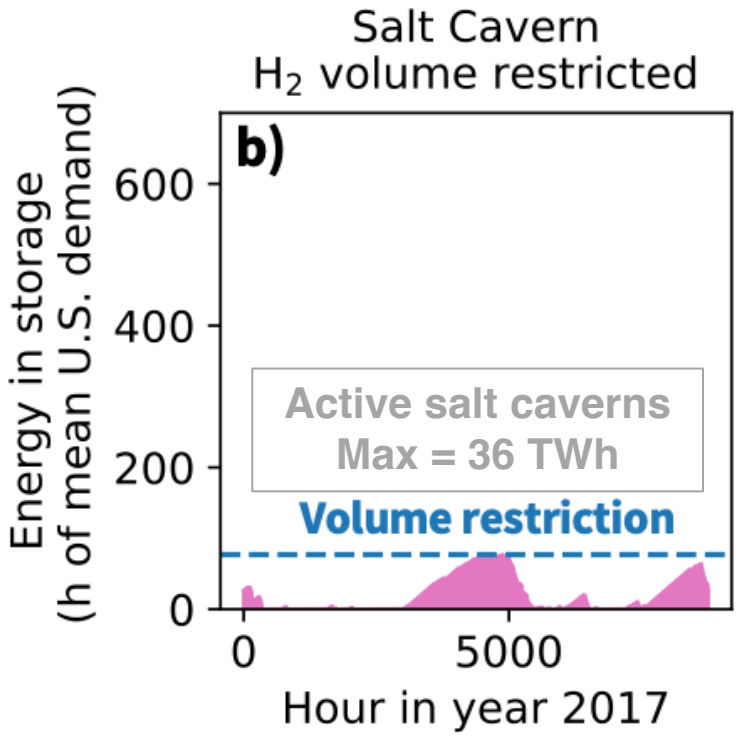


~175 TWh in least-cost reliable wind-solar-H_2-battery system in the U.S.
However, system costs are quite *insensitive* to that value if we constrain it.

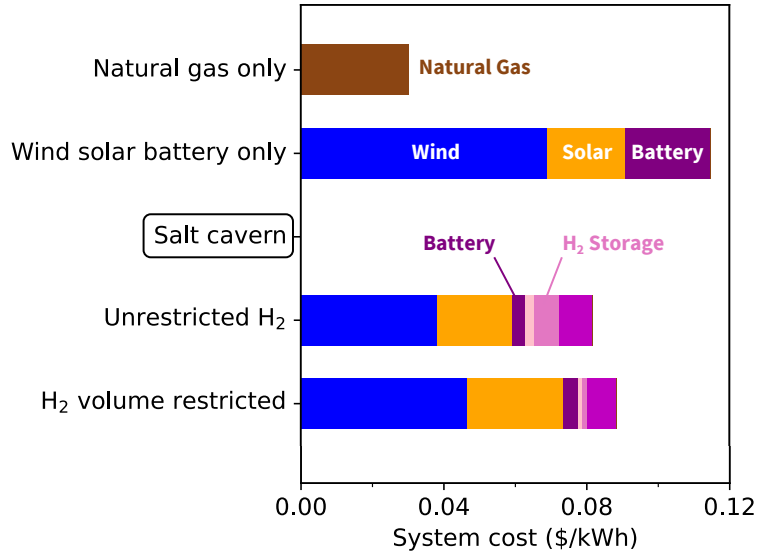
Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

Even with tight capacity limits in salt caverns, H_2 storage still reduces system costs





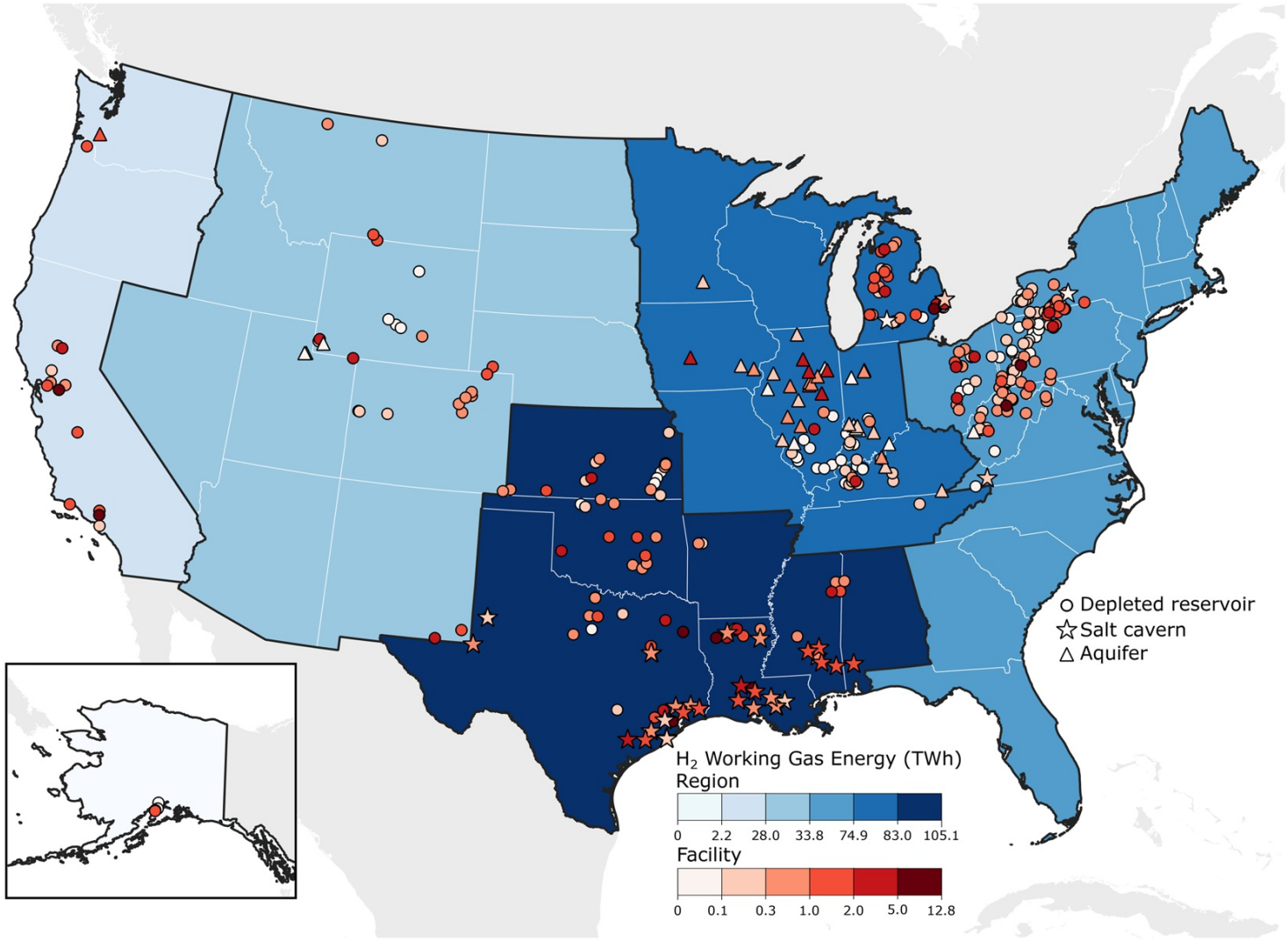
System cost impact of salt cavern volume restriction:



Salt cavern + Depleted reservoirs
327 TWh (SHASTA)

Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

Ample capacity in *existing* natural gas infrastructure



SHASTA National Lab Project: Lackey, G. et al. *GRL*, **2023**.

How much storage is optimal?

Approx. Total needed:
~175 TWh (Dowling et al.)
of hydrogen working gas

How much storage is available in active natural gas storage facilities?

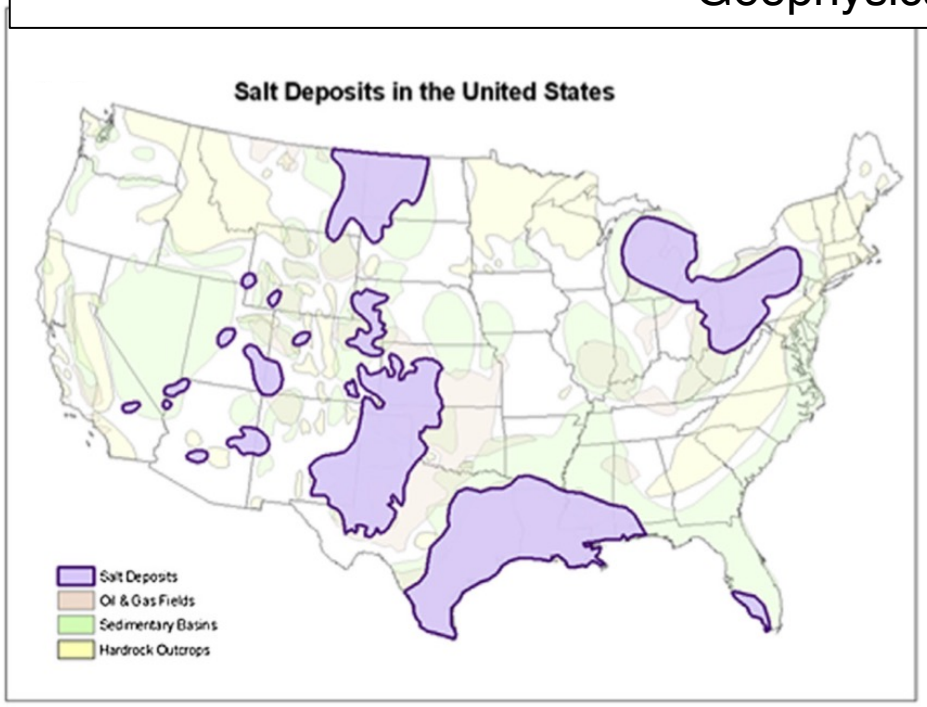
Salt Caverns: 36 TWh
Depleted reservoirs: 291 TWh
Total available: 327 TWh (SHASTA)
of hydrogen working gas

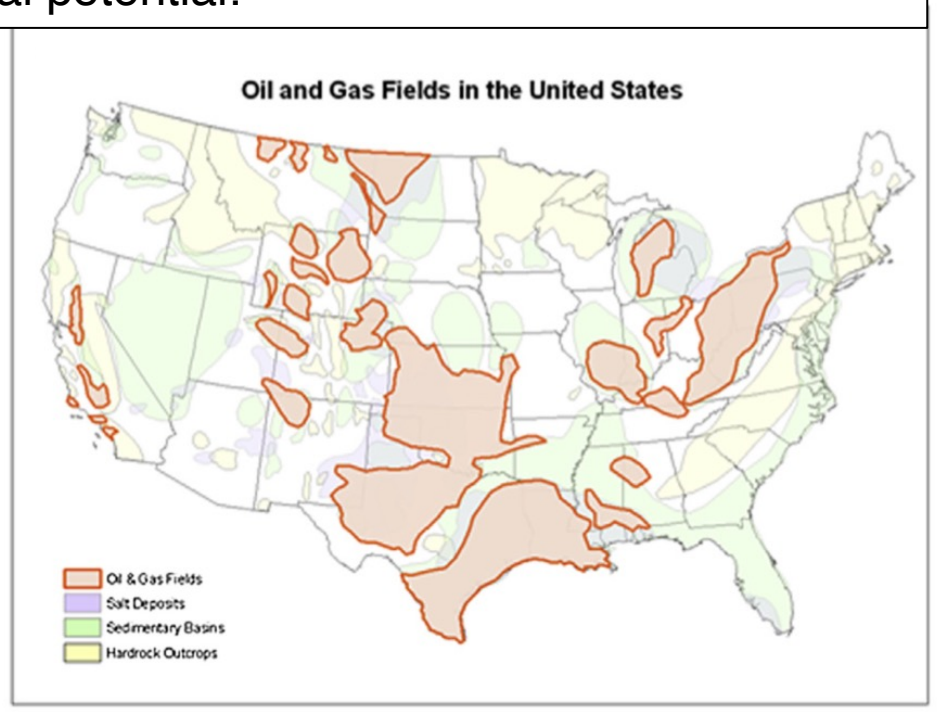
Repurposing about half the volume available in active U.S. natural gas storage facilities for pure hydrogen would provide ***national-scale seasonal energy storage*** in a 100% reliable wind-solar-hydrogen electricity system.

Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

Vast potential for *new* geologic hydrogen energy storage

Geophysical potential:





Salt Caverns
Pro: Commercially proven for H_2,
Con: Constrained Capacity

Depleted Reservoirs
Pro: Abundant capacity
Con: Emerging technology for H_2

Figure - Sandia National Laboratories
Lord et al. International Journal of Hydrogen, 2014

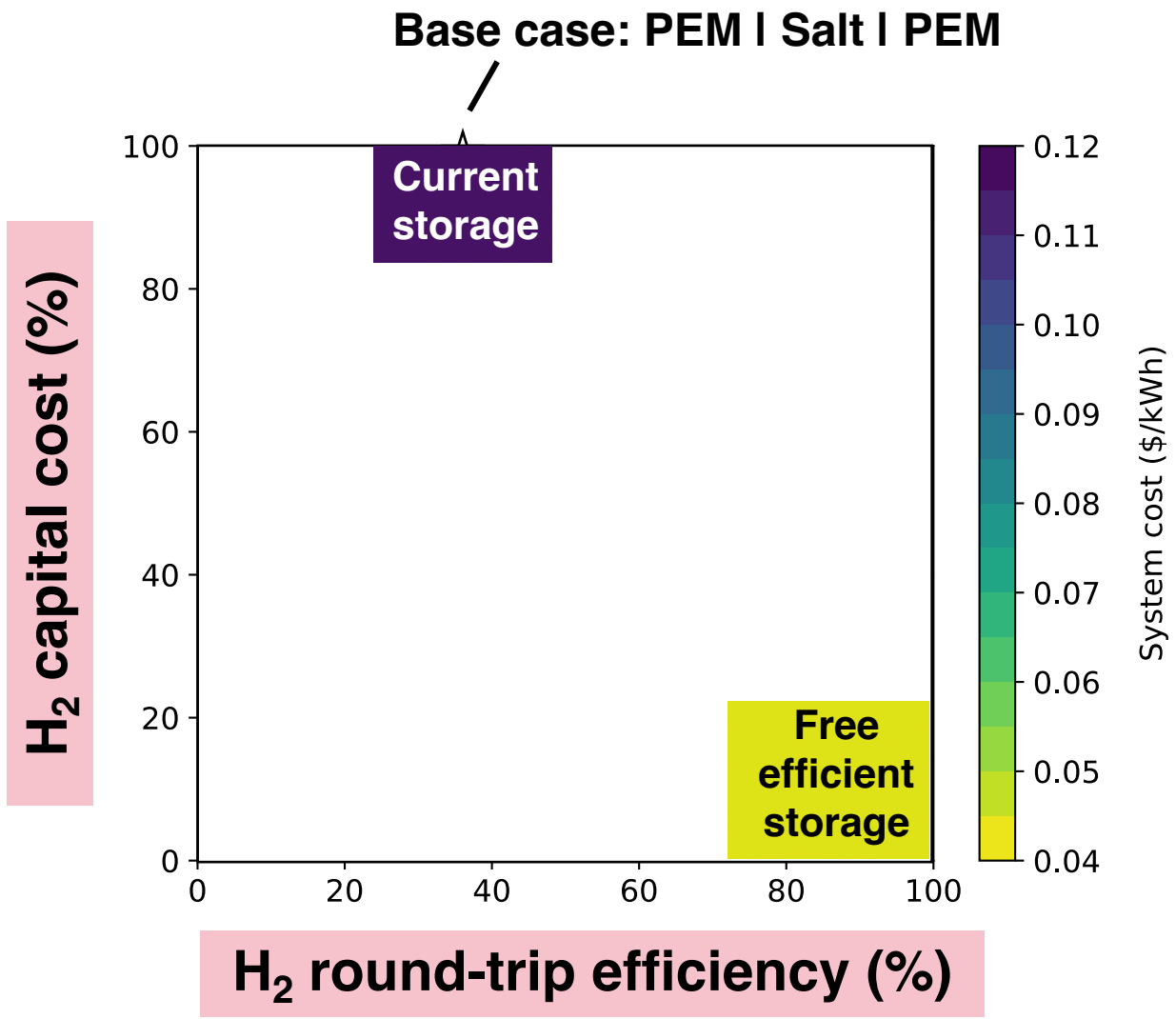
Outline

Which hydrogen energy storage innovations are most valuable for reducing reliable wind and solar system costs?

Constraints and Innovation

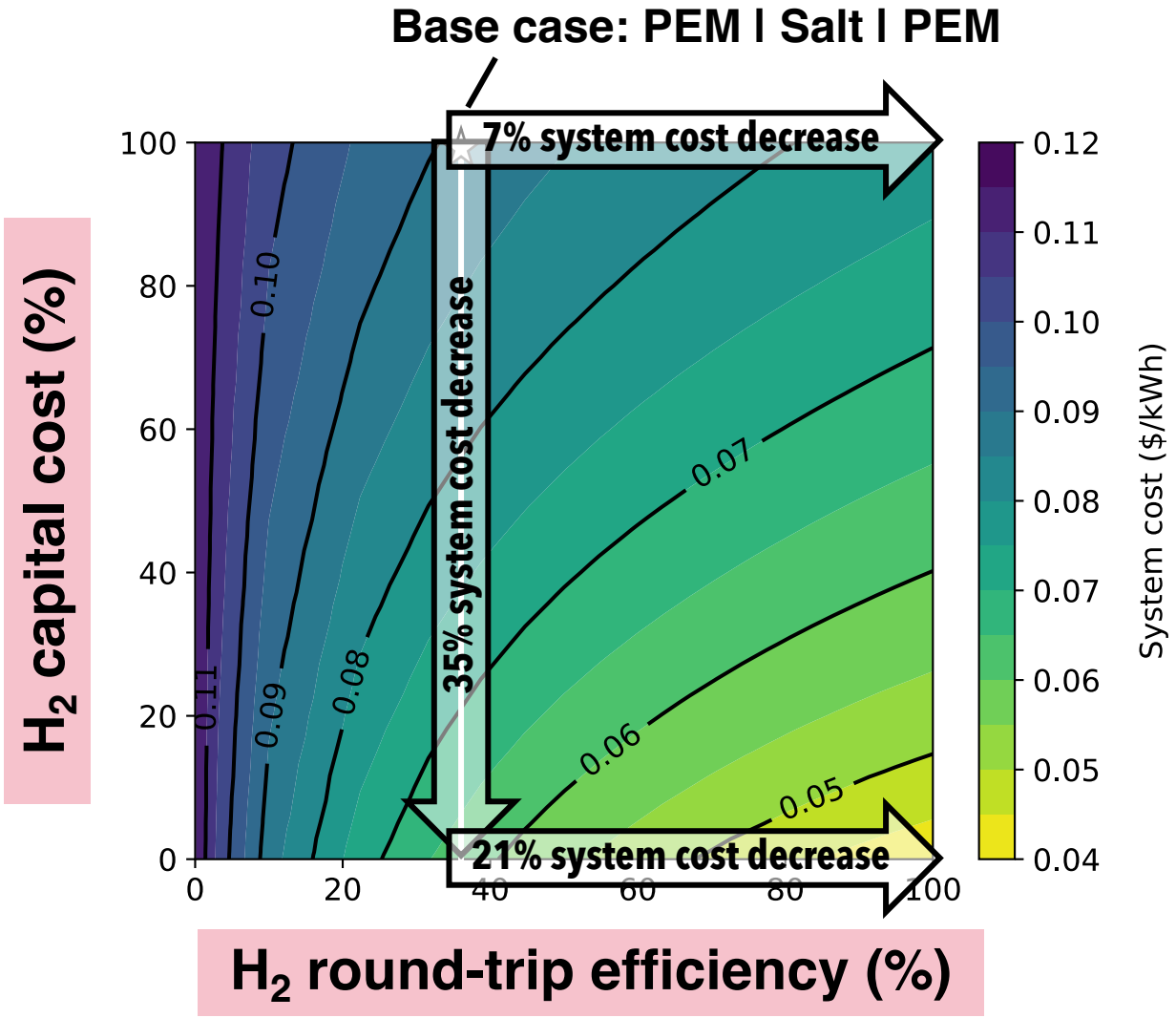
- **Underground Storage Constraints**
- **High- and Low-Value Innovation**
- **Shift in Materials Chemistry Focus**

Which innovation is more valuable for hydrogen storage systems? Capital cost or efficiency improvements?



Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

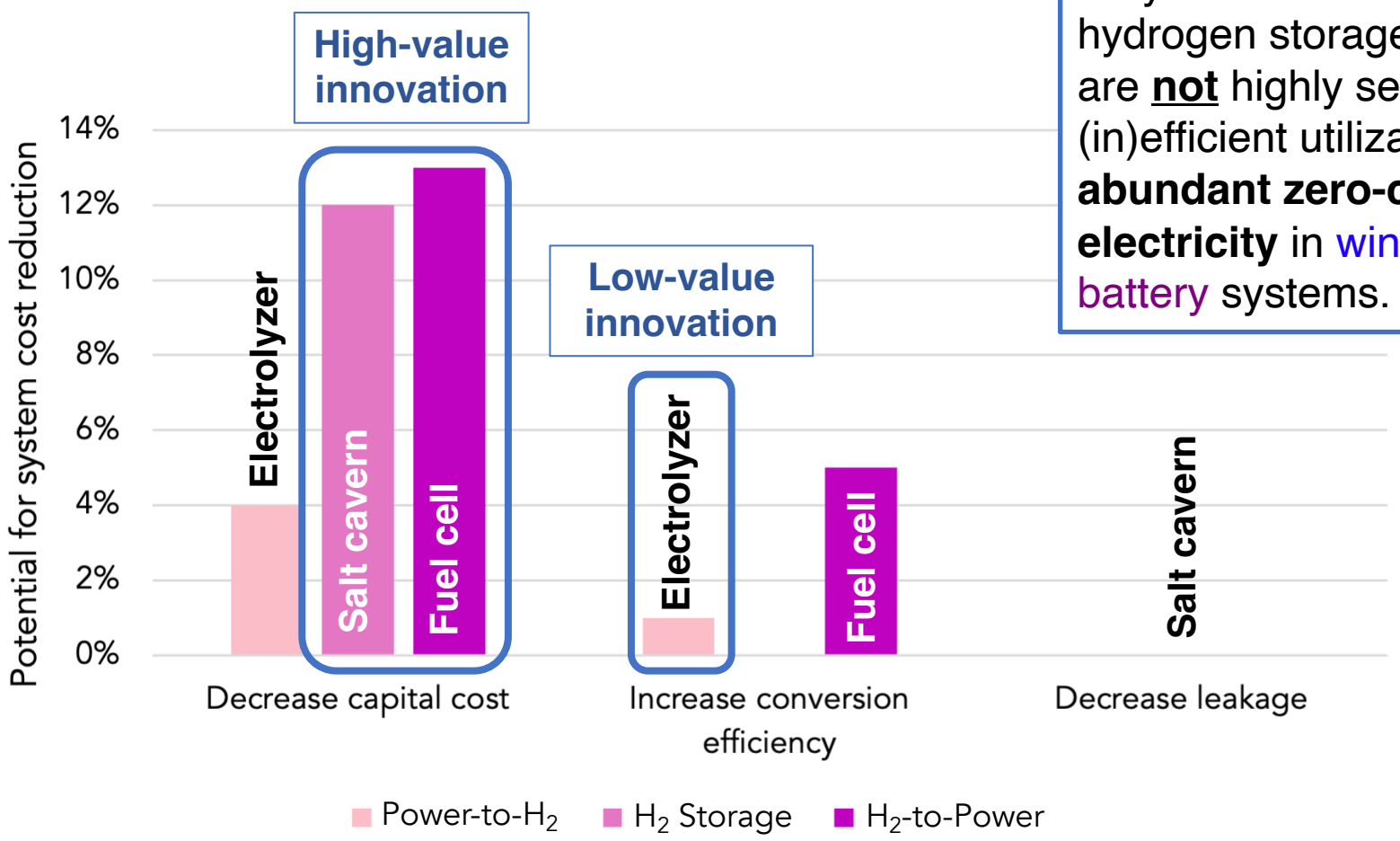
Capital cost improvements were more valuable than efficiency improvements



Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

High-value innovation: Improve fuel cell capital cost or salt cavern cost
Low-value innovation: Improve electrolyzer efficiency

Starting from base case: PEM | Salt | PEM

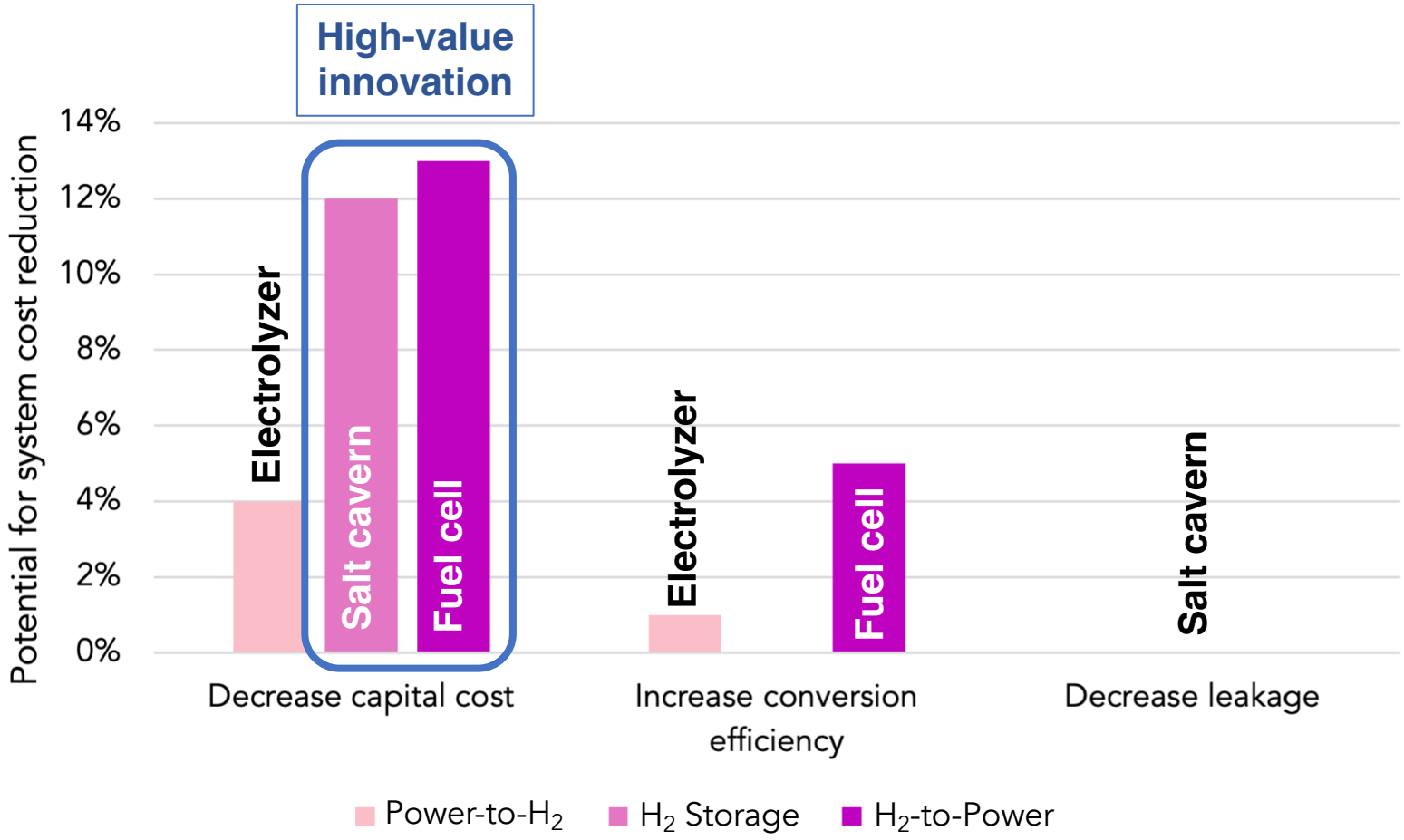


Why? **Due to curtailment**, hydrogen storage systems are **not** highly sensitive to (in)efficient utilization of **abundant zero-cost electricity** in wind-solar-battery systems.

Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

For any long-duration energy storage technology…
High-value innovation:
Improve energy storage capital cost or discharger capital cost

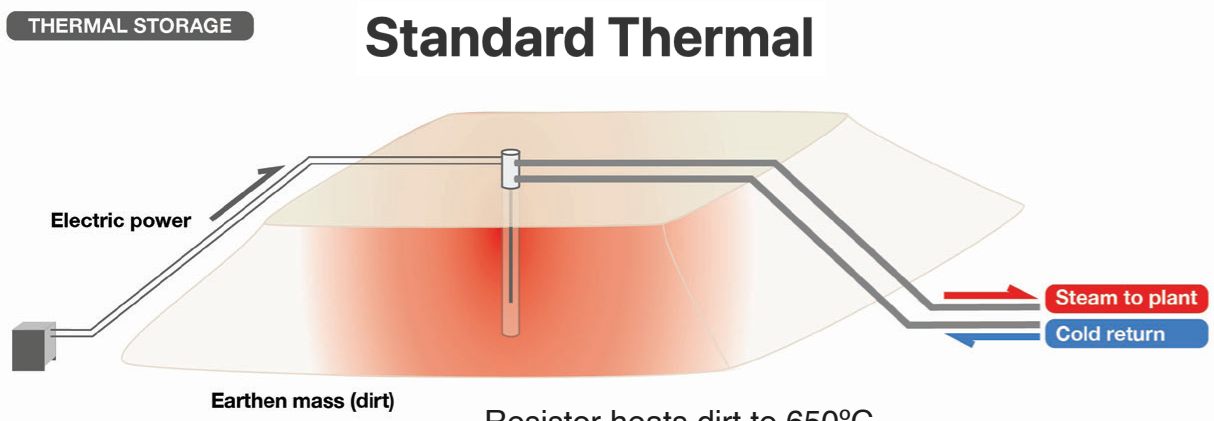
Starting from base case:
PEM I Salt I PEM



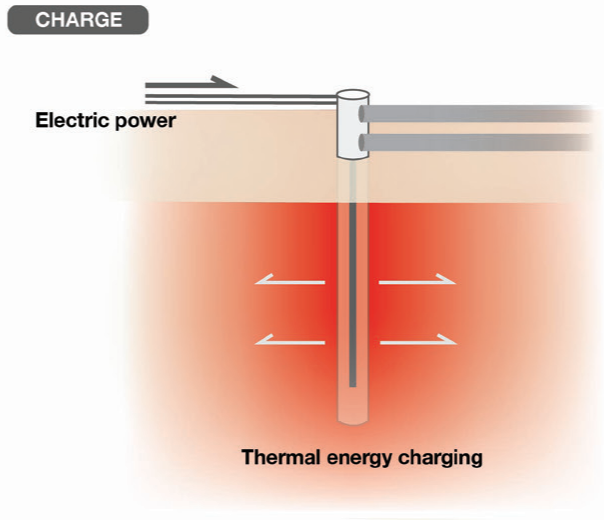
Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

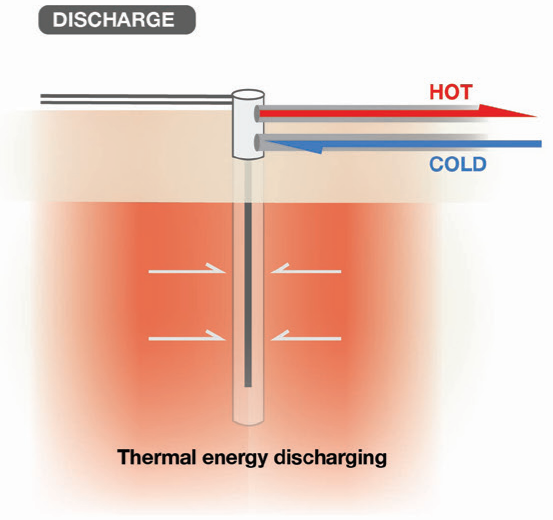
Dirt-cheap energy storage!

- **Thermal energy storage in dirt uses soil or rock to store energy at low energy capacity costs ($0.01/kWh).**
- Grid electricity heats water in pipes, which transfer heat to the surrounding dirt.
- This stored thermal energy can then be used to repower steam turbogenerators at decommissioned coal power plants. **Repurposing means a very low discharger cost of ($250 /kW).**



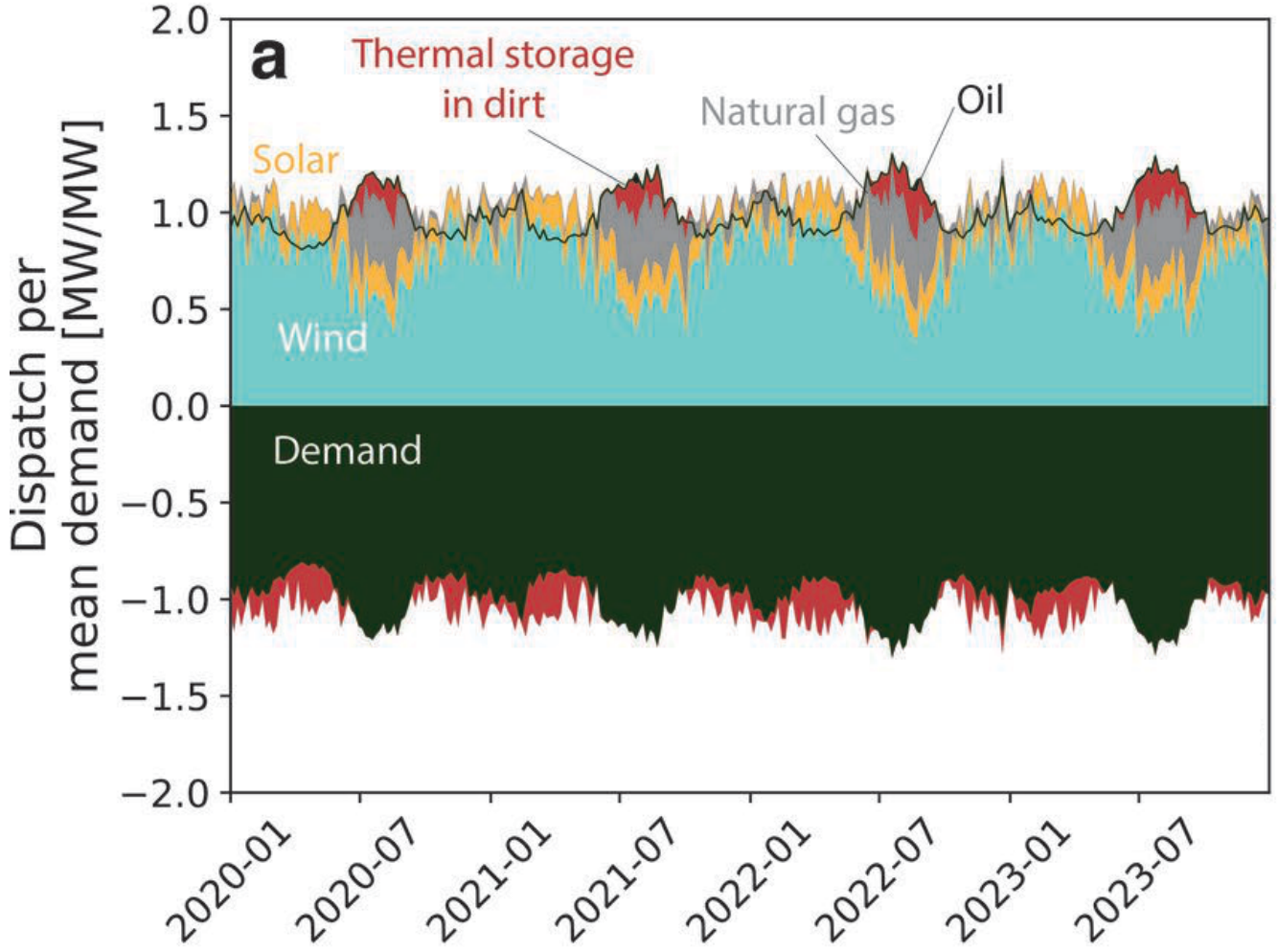
Resistor heats dirt to 650°C
Steam heated by dirt to 300°C





Wongel, Alicia, Jacqueline A. Dowling, Lei Duan, Austin Vernon, Ian S. McKay, and Ken Caldeira. "Thermal Energy Storage in Dirt for Repowering Decommissioned Coal Plants." Findings, **2025**.

Thermal energy storage in dirt fills a seasonal storage role *without an emissions constraint!*



- In electricity systems reliant on wind, solar, and natural gas generation, ***thermal storage in dirt could play a key role in addressing seasonal electricity demand challenges***, increasingly so with larger shares of wind and solar generation.
- Natural gas and thermal energy stored in dirt provide electricity primarily to meet seasonal residual demand challenges ***posed by wind lulls and concurrent demand peaks***.

Wongel, Alicia, Jacqueline A. Dowling, Lei Duan, Austin Vernon, Ian S. McKay, and Ken Caldeira. "Thermal Energy Storage in Dirt for Repowering Decommissioned Coal Plants." Findings, **2025**.

Outline

How can we develop electrolyzer catalysts specifically for energy storage applications in wind and solar systems?

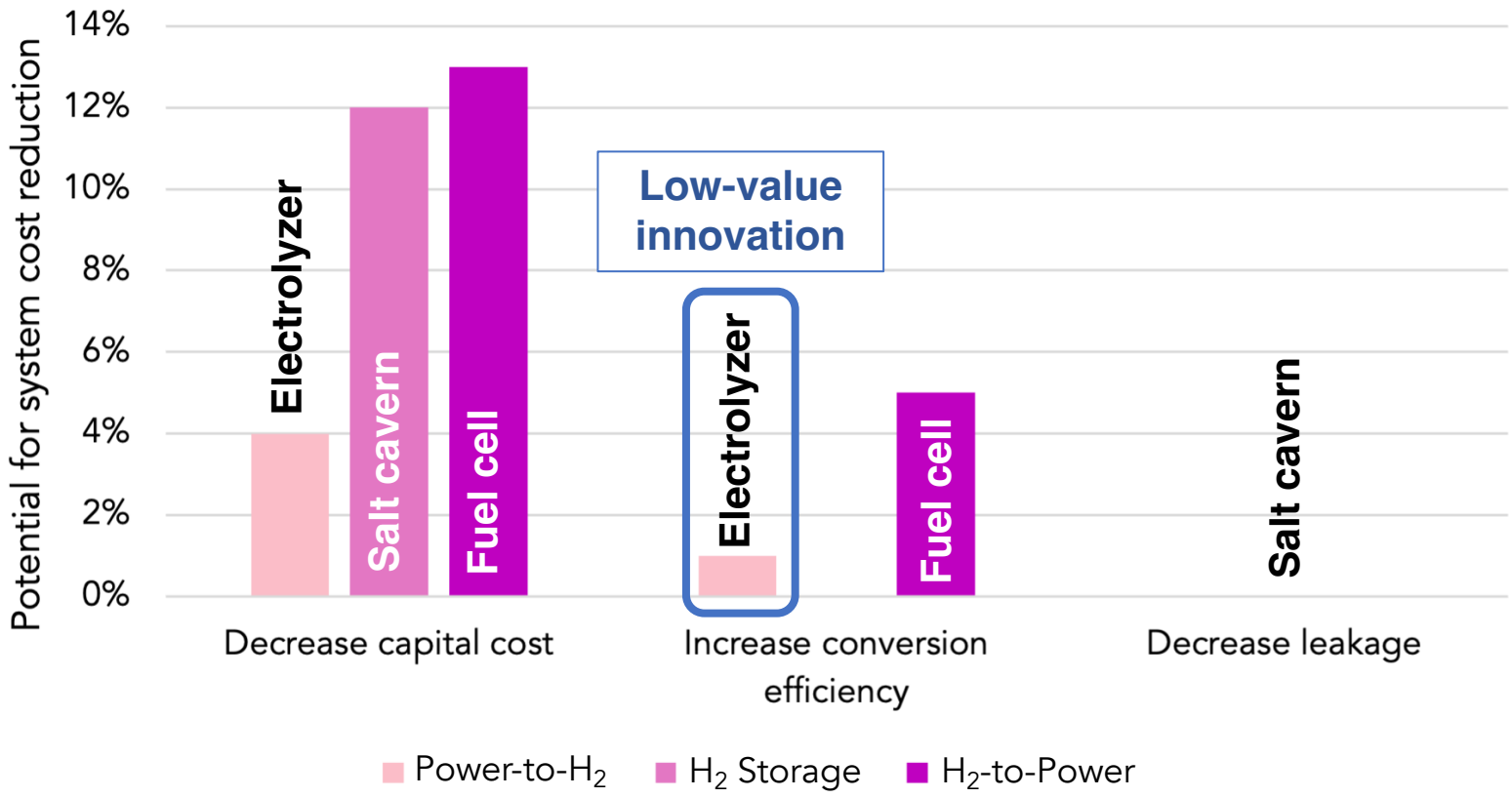
Constraints and Innovation

- **Underground Storage Constraints**
- **High- and Low-Value Innovation**
- **Shift in Materials Chemistry Focus**

Low-value innovation: Improve electrolyzer efficiency

Can we take advantage of this?

Starting from base case: PEM I Salt I PEM



Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

Commercial proton-exchange membrane (PEM) electrolyzers depend on precious metal catalysts

Power Conversion

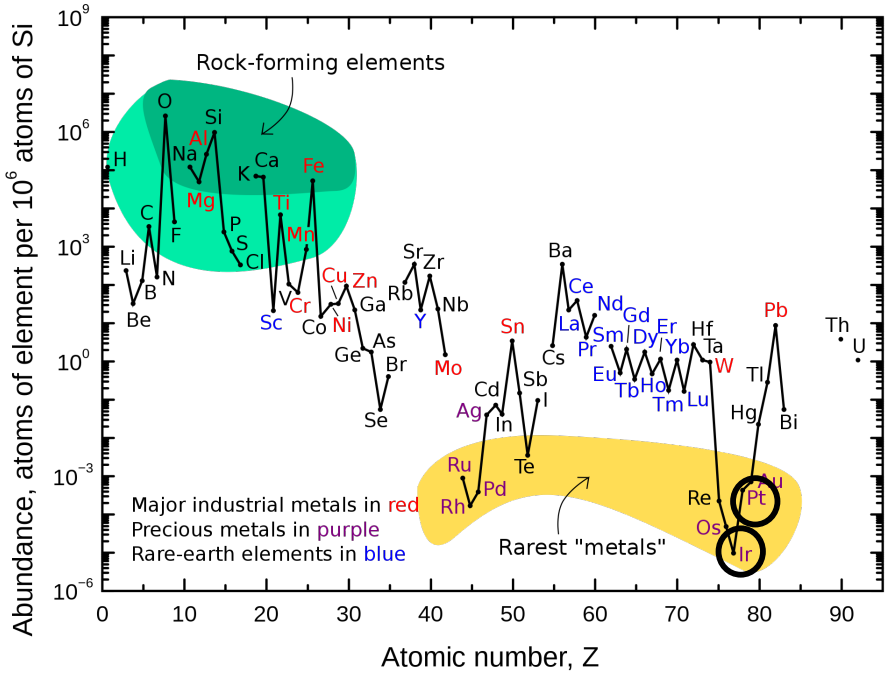
Electrolyzer

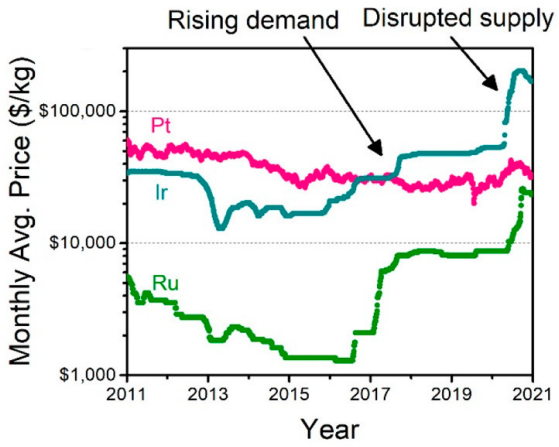
Charging

PEM electrolyzer

Water splitting:

$H_2O \rightarrow H_2 + {}^1/_2O_2$

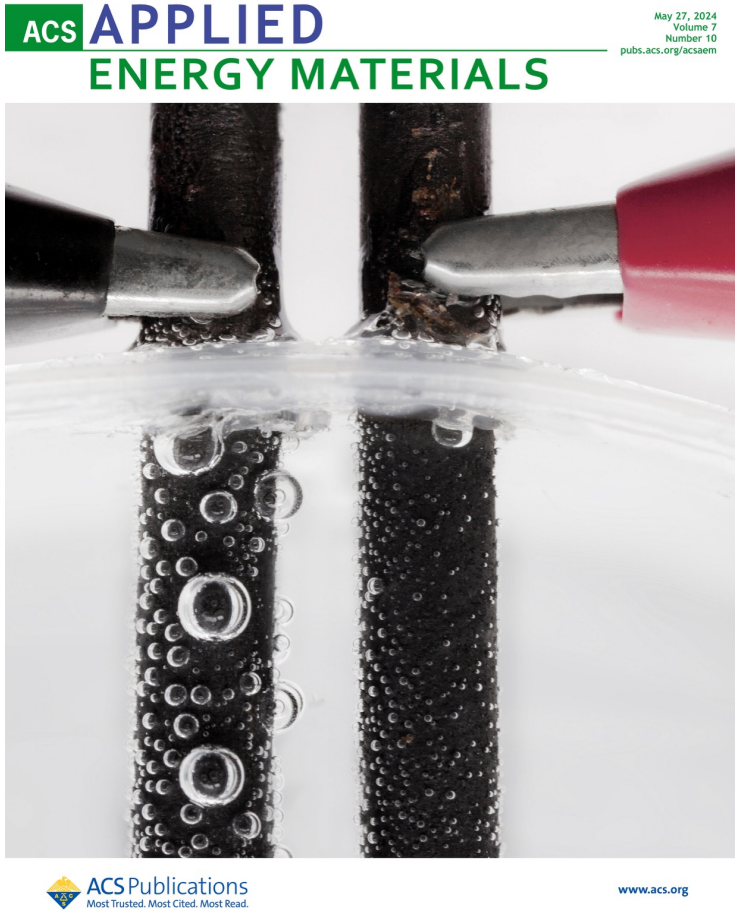


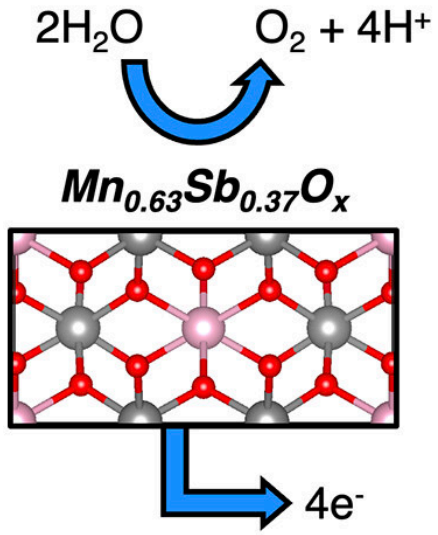


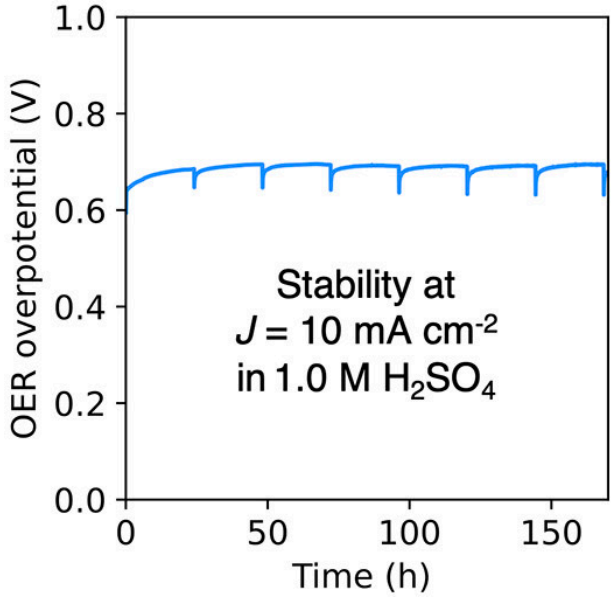
Iridium demand and volatile prices pose a risk to scale-up of PEM electrolyzers

Hubert et al., *ACS Energy Lett.* **2022**.

Explicit targeting of a lower-efficiency, but more earth-abundant catalyst







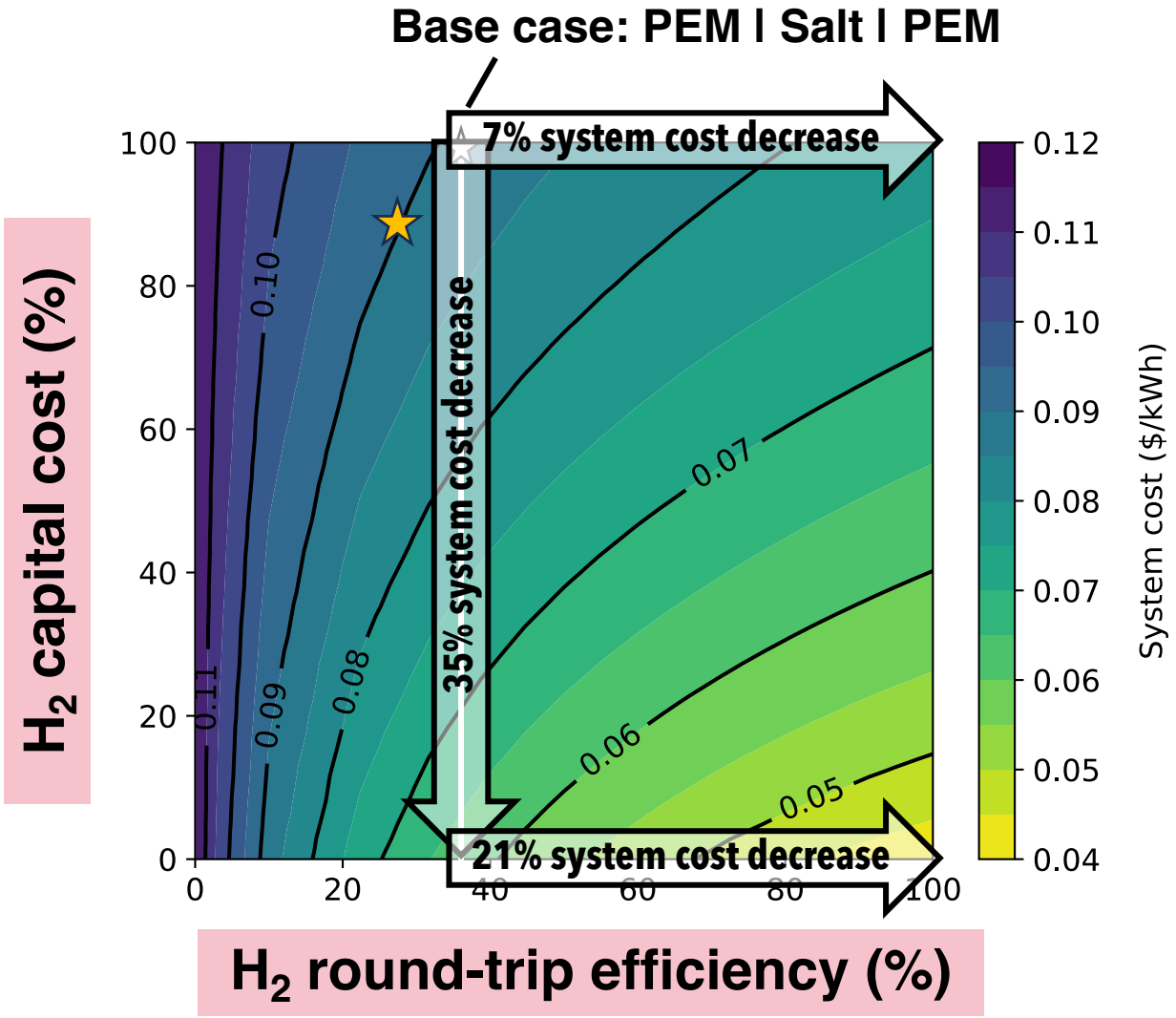
Represents a shift in materials chemistry focus guided by system-level analysis.

Dowling et al., Catalysis of the Oxygen-Evolution Reaction in 1.0 M Sulfuric Acid by Manganese Antimonate Films Synthesized via Chemical Vapor Deposition *ACS Appl Eng Mat.*, **2024.**

Where would this new catalyst be on the map?

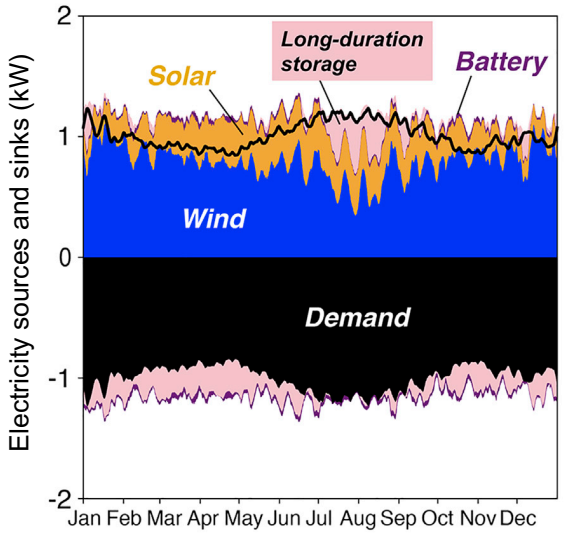
Potentially similar total system cost, but not as dependent on critical materials.

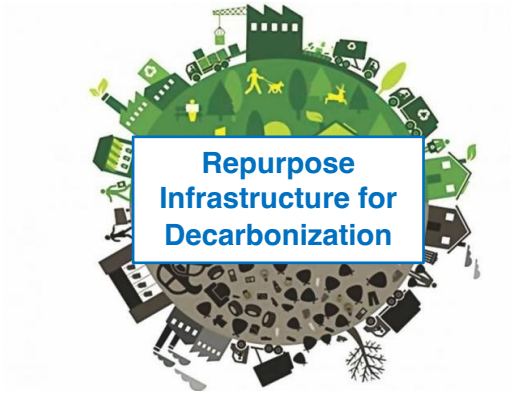
Potential improvement on **energy security** objectives.



Dowling et al., Opportunities and Constraints of Hydrogen Energy Storage Systems. *EREN,* **2024**.

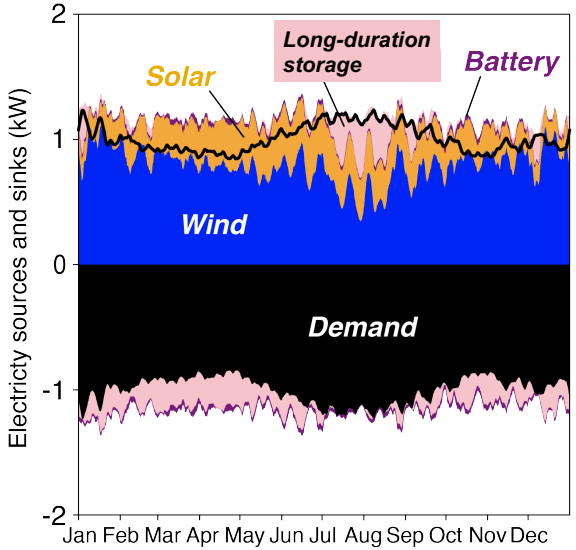
Wind and solar constraints guide energy storage opportunities





Conclusions:

Long-Duration Energy Storage Opportunities



Dowling et al., *Joule,* **2020**.

Dowling et al., *EREN,* **2024**.

Dowling et al., *ACS Appl Eng Mat.*, **2024.**

Li*, Virgüez*, Dowling* et al., *ES&T,* **2024**.

Long-Duration Energy Storage

- **Geologic Hydrogen Storage**

  Long-duration energy storage reduces the cost of reliable wind-solar-battery systems by **filling seasonal and multi-year storage functional roles**.

- **Energy Storage Portfolios**

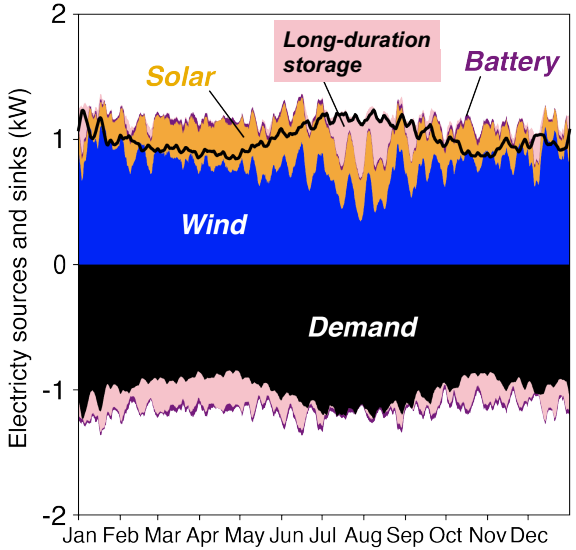
  Long-duration energy storage **may also satisfy short-term storage needs**.

- **Competition with Natural Gas**

  Geologic hydrogen storage competes with natural gas in deep decarbonization scenarios due to its **low energy capacity costs**.

Conclusions:

Long-Duration Energy Storage Opportunities



Dowling et al., *Joule,* **2020**.

Dowling et al., *EREN,* **2024**.

Dowling et al., *ACS Appl Eng Mat.*, **2024.**

Li*, Virgüez*, Dowling* et al., *ES&T,* **2024**.

Constraints and Innovation

- **Underground Storage Constraints**

  Half of the active natural gas storage sites in the U.S. **could beneficially be repurposed** for national-scale seasonal energy storage.

- **High- and Low-Value Innovation**

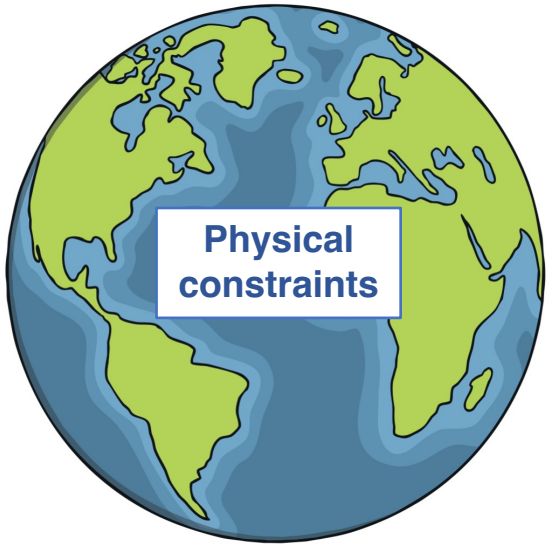
  Due to curtailment, innovation in hydrogen storage system capital cost is **more valuable than efficiency innovation** for energy storage applications in wind and solar-based electricity systems.

- **Shift in Materials Chemistry Focus**

  Explicitly targeted a **lower-efficiency but more earth-abundant** catalyst guided by system-level analysis.

Interdisciplinary Approach to Energy Storage PhD

1. Analyze resource constraints



Climate Science

Wind and solar constraints

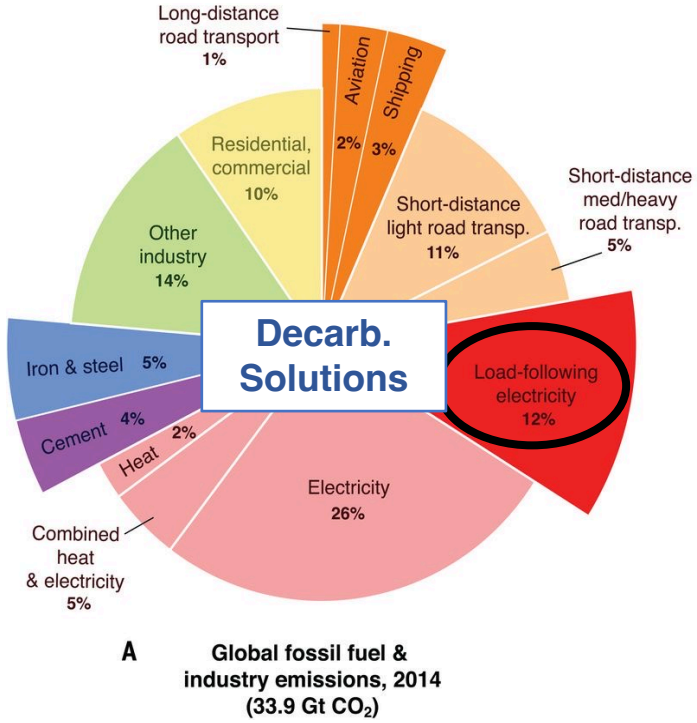
2. Guide technology innovation

Electrochemistry

Energy storage innovation

Macro-energy systems

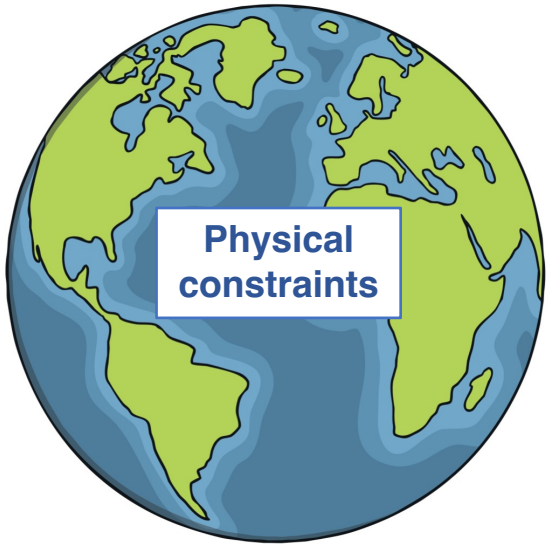
3. Target decarbonization solutions



Load-following electricity

Interdisciplinary Approach to Clean Heat Postdoc

1. Analyze resource constraints



Earth System Science

Temperature constraints

Steve Davis

2. Guide technology innovation

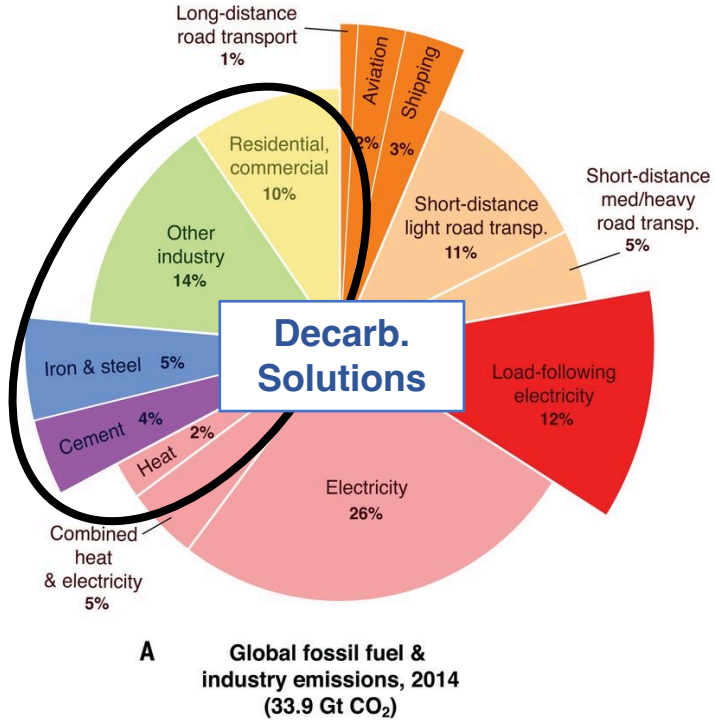
Energy Science & Engineering

Heat pump innovation

Adam Brandt
Inês Azevedo

Data analysis

3. Target decarbonization solutions



Net-zero emissions heat

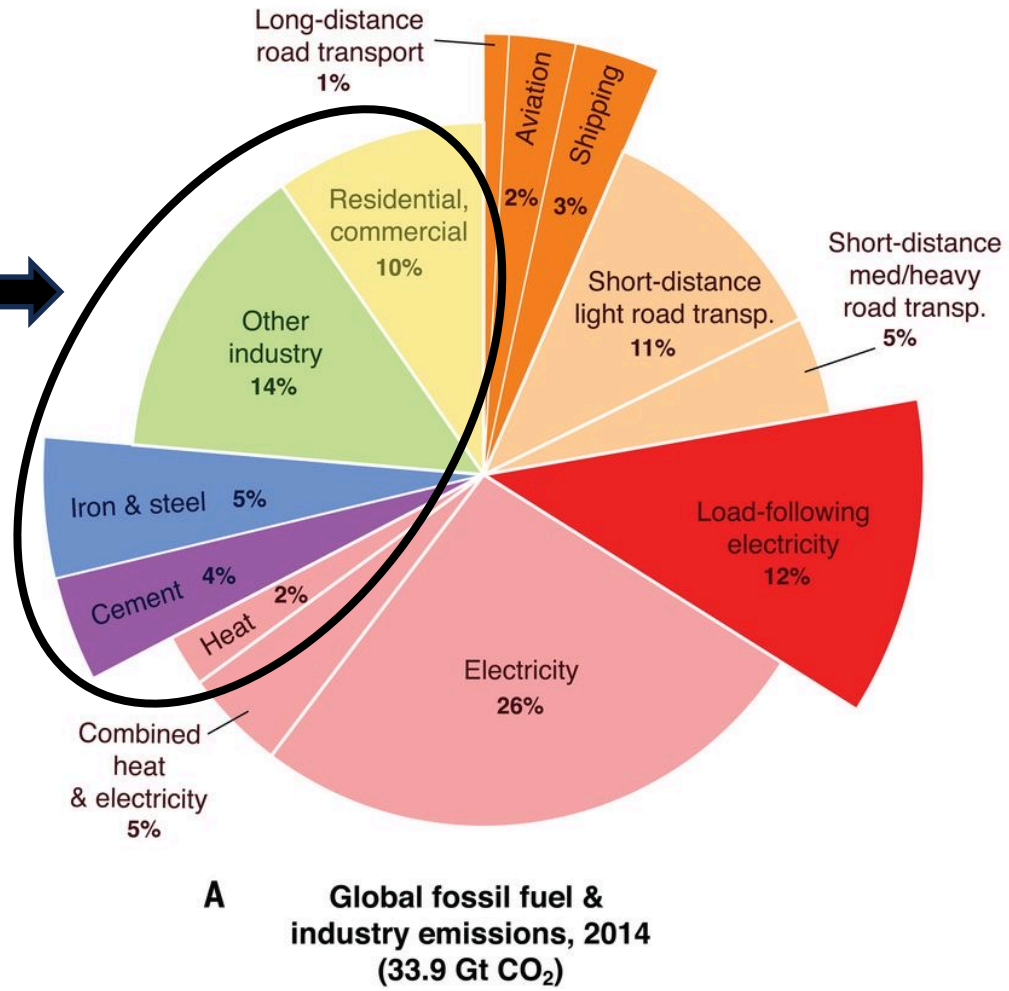
Net-zero emissions heat

Current work

Net-zero emissions heat

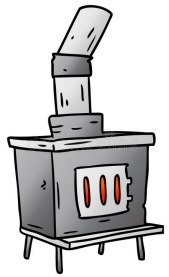
40% of global & U.S. emissions

Span industrial, commercial, and residential sectors



A **Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)**

What does it cost to decarbonize U.S. heat demand in buildings and industry?



Buildings

Industry

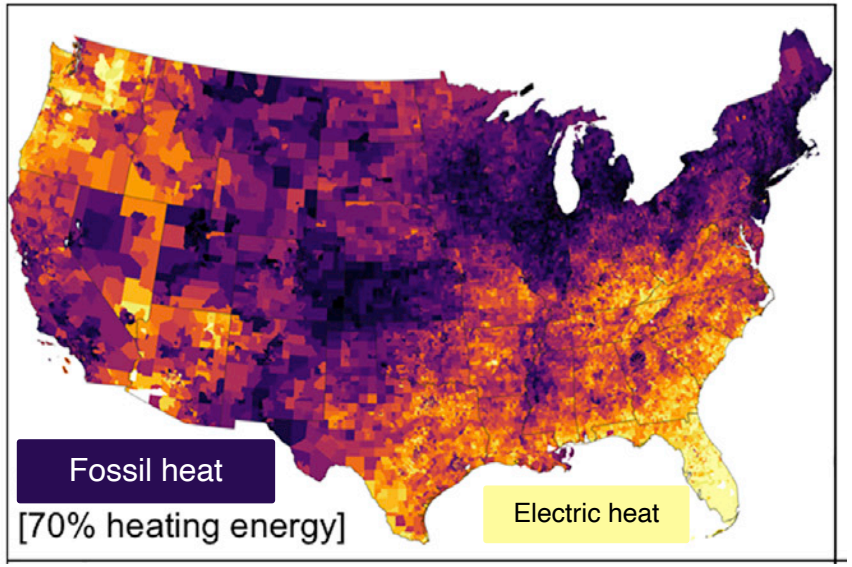
★ Today's focus

Dimitri Saad

Davis et al., Net-Zero Emissions Energy Systems. *Science,* **2018**.

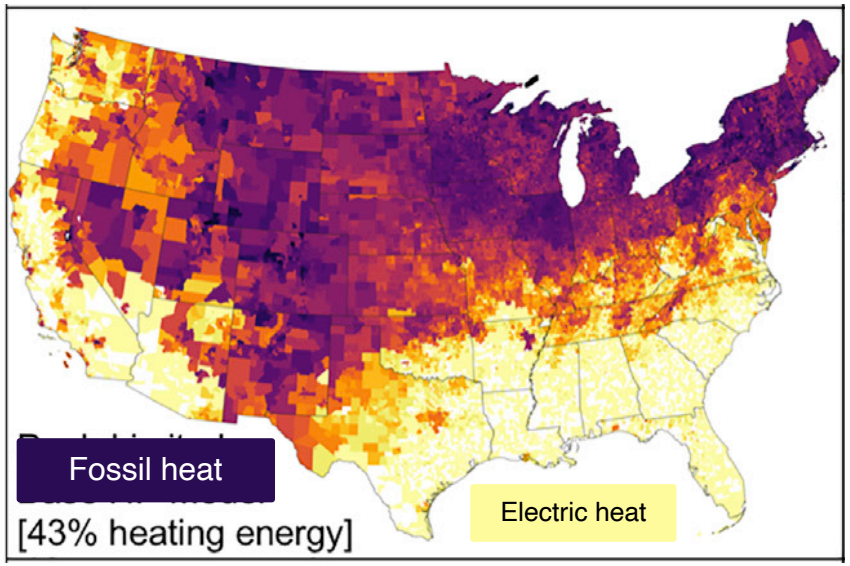
Specific heat demands may be difficult-to-decarbonize

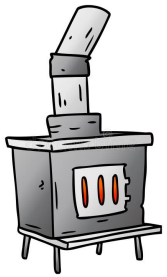
Fraction of space heating energy from fossil fuels



Add heat pumps, but no new electricity distribution

Fraction of space heating energy from fossil fuels





Buildings

Electricity distribution upgrades pose challenges for decarbonizing building space-heating in cold climates via **heat pumps**.

Knowledge Gap: No cost estimation.

Dataset: Census-tract level, hourly temperature-derived building heat demand over 10 years. (Waite & Modi)

Waite & Modi, Electricity Load Implications of Space Heating Decarbonization Pathways. *Joule*, **2020**.

Key Questions

Net-zero emission heat

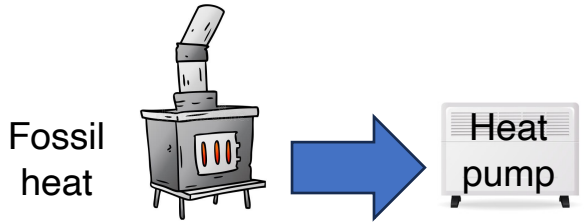
What does it cost to decarbonize heat U.S. heat demand in buildings and industry?

- What are the key cost drivers?
- Are there key thresholds in cumulative abatement costs?
- What are the key sensitivities?

Data analysis of difficult-to-decarbonize heat demands to guide technology innovation priorities

Primary Tool: Abatement Cost Equation

Considers a technology replacement cost and emissions change



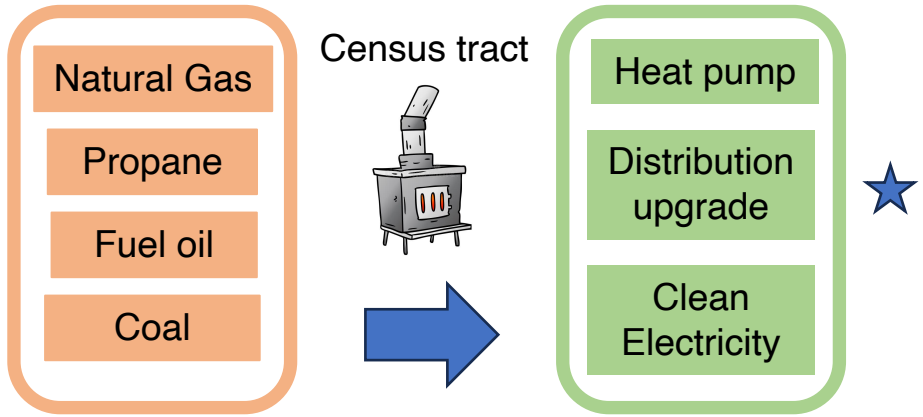
Buildings in a census tract

$$Abatement\ Cost = \frac{Cost_{new} - Cost_{old}}{Emissions_{old} - Emissions_{new}}$$

Negative (-) abatement costs identify locations where heat pump electrification saves money.

Large positive (+) abatement costs identify difficult-to-decarbonize heat demands guiding innovation priorities.

Cost and Emissions Assumptions



Residential heat pump CapEx cost from PyPSA: $1225/kW

2023 State-level retail electricity prices (EIA)

Utility-specific distribution upgrade costs (FERC, EIA)

Census tract fossil fuel mix	Price	
Natural gas	14.83	$/ MMBtu
Propane	29.16	$/ MMBtu
Fuel oil, kerosene	27.65	$/ MMBtu
Coal	5.12	$/ MMBtu

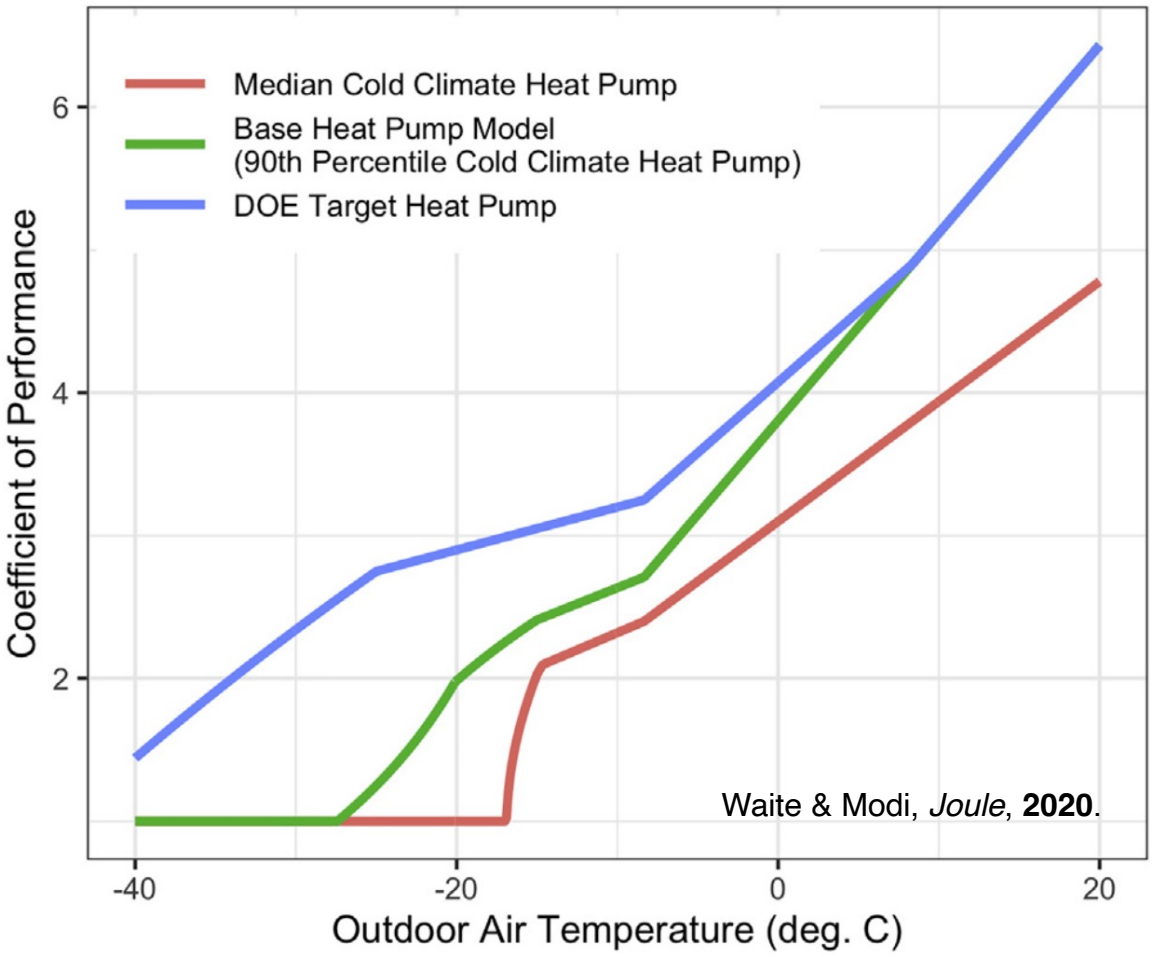
Building Abatement Cost =

$$\frac{\text{Heat pump and distribution CapEx and Electricity OpEx} - \text{Fuel OpEx of existing building heating fossil fuel}}{\text{Emissions of existing building heating fossil fuel} - \text{Emissions of heat pumps with clean electricity}}$$

Census tract fossil fuel mix	Emissions	
Natural gas	0.058	tCO2/MMBtu
Propane	0.069	tCO2/MMBtu
Fuel oil, kerosene	0.082	tCO2/MMBtu
Coal	0.106	tCO2/MMBtu

Assume electricity emissions intensity: 0 tCO_2/kWh

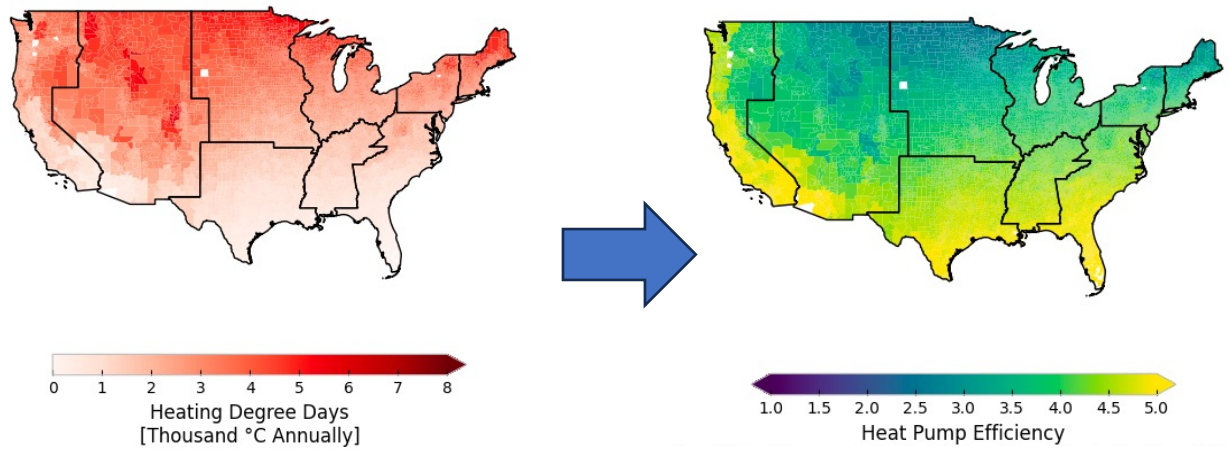
Temperature data constrains heat pump efficiency



- We assume performance of the top 90% best heat pumps currently commercially available (Green line).
- Linear approximation:

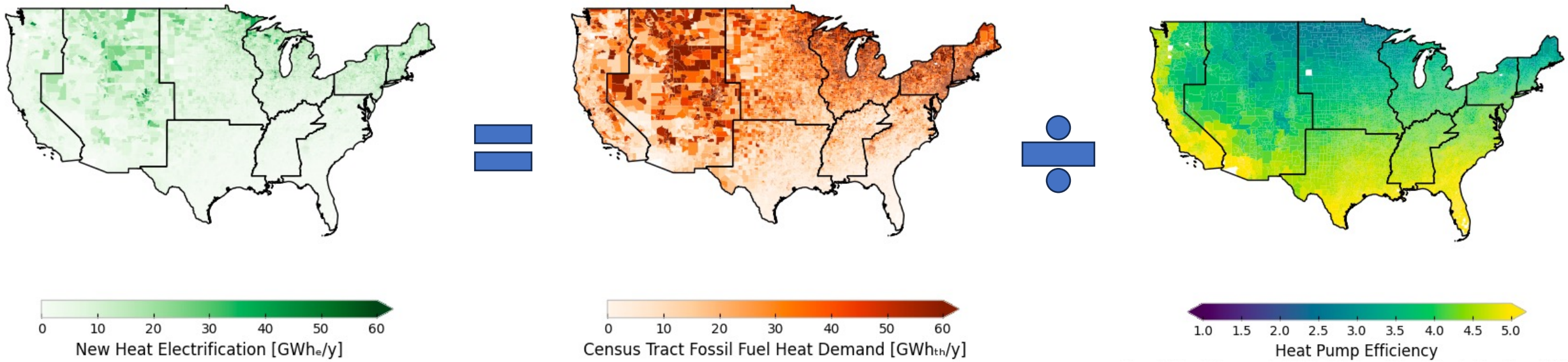
$$Heat\ Pump\ Efficiency = 0.111 * Temperature + 4.0$$

- Average heat pump efficiency weighted by new electricity load is 4.



- In very cold weather below -27 °C, heat pump efficiency = 1.
- Target indoor temperature is 18 °C, or 65 °F .

Heat pump electrification *reduces total energy* demand for heat

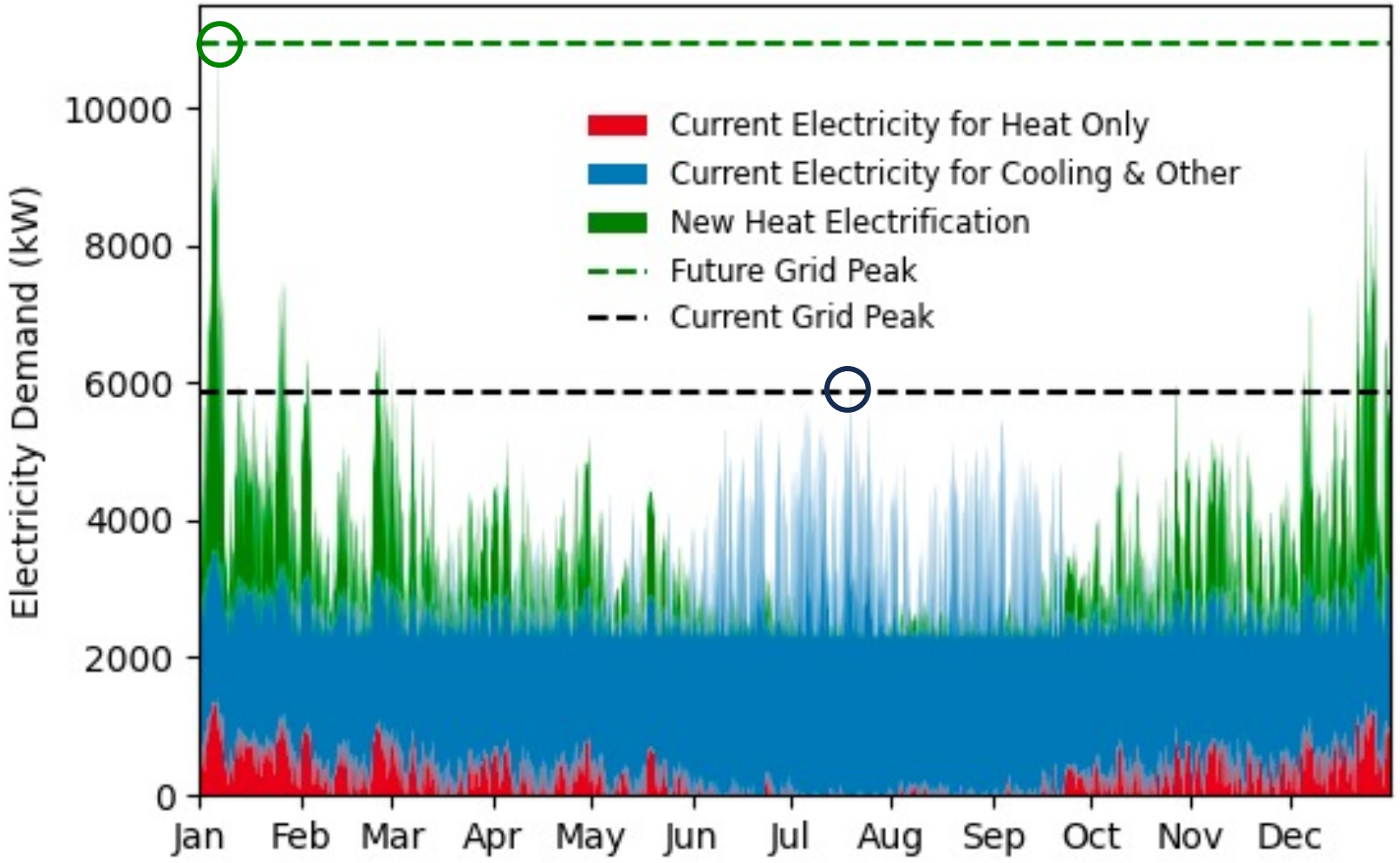


$$New\ Heat\ Electrification\ [kWh_e] = \frac{Fossil\ Heat\ Demand\ [kWh_{th}]}{Heat\ Pump\ Efficiency\ [\frac{kWh_{th}}{kWh_e}]}$$

- Average heat pump efficiency weighted by new electricity load is 4.

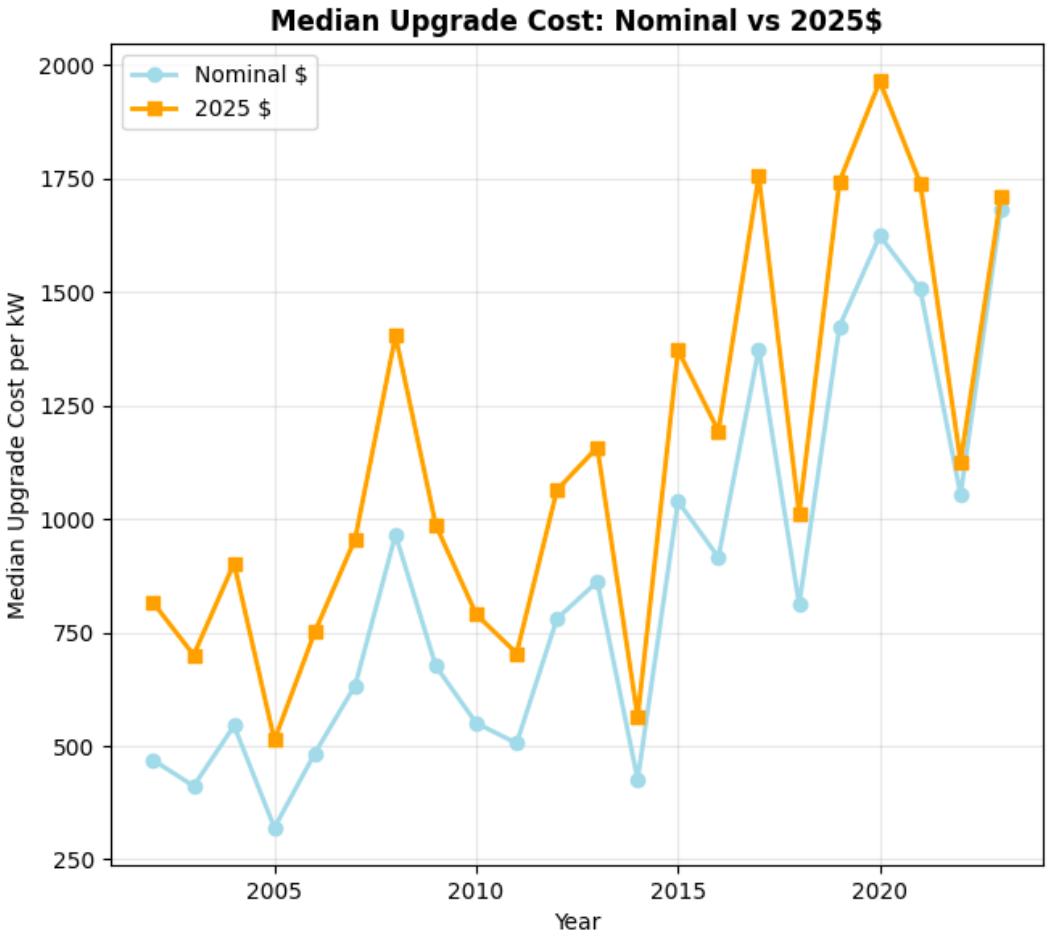
- ***Total energy demand for heat is lower*** because heat pumps are more efficient than fossil fuels.

However, heat pump electrification can *increase peak load*



- Heat electrification increases peak load ***massively*** in an example CO census tract in 2017.
- Hourly peak difference due to heat electrification determines distribution upgrade need.

Distribution upgrade prices are expensive and have been rising



Distribution upgrade prices are rising faster than inflation. These prices include poles, wires, undergrounding, & transformers.

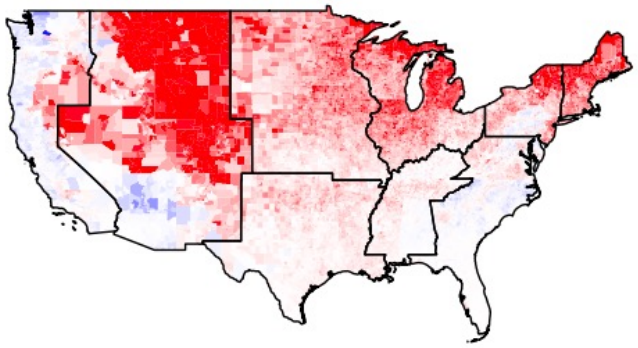
To estimate utility-specific distribution upgrade prices ($/kW):

- Match year-over-year CapEx additions from FERC Form 1 ($) with peak demand from EIA-861 as a proxy for distribution capacity (kW).

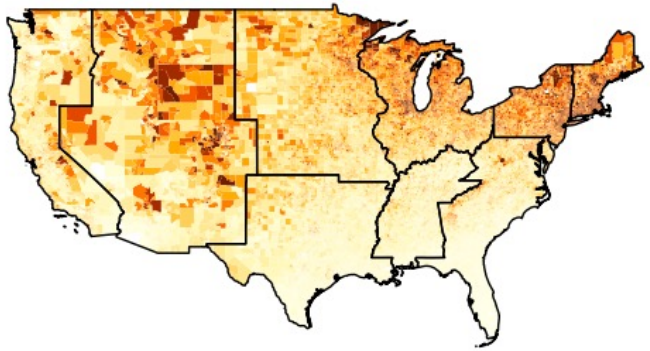
Knowledge Gap: *Heat pump electrification studies rarely include distribution upgrade costs, and potential distribution investment needs haven't yet been estimated nationwide at the census tract level.*

Check out recent Shift Key Podcast on this topic.

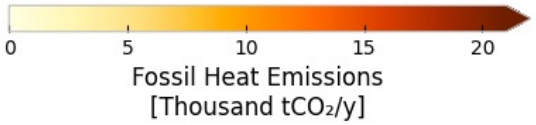
Initial Results: Electrification of Fossil Heat in Buildings

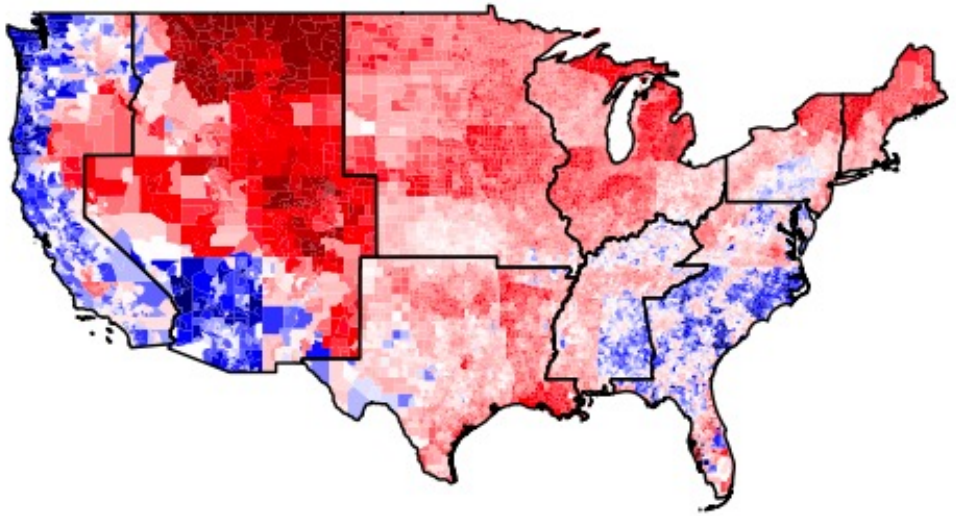


Numerator

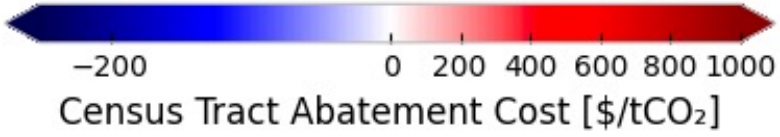


Denominator





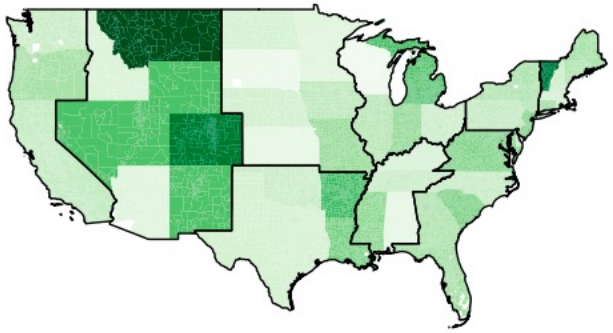
Abatement Cost



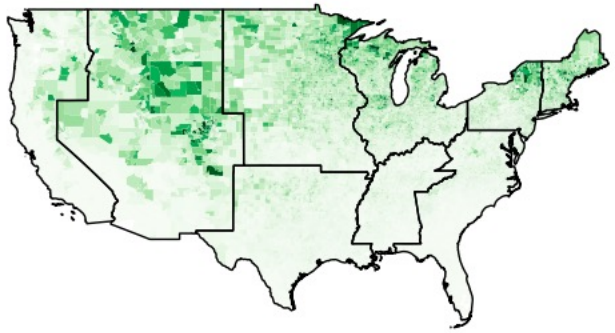
$$Abatement\ Cost = \frac{Cost_{clean} - Cost_{fossil}}{Avoided\ Emissions_{fossil}}$$

- ***Many census tracts across the U.S. can electrify building heating at a profit (blue tracts) or cost-neutrally (white tracts)!***
- Carbon abatement costs for building heat electrification are highest (red tracts) in the Mountain West division, where distribution investments are greatest.
- Abatement costs, weighted by emissions avoided, average ***$230/tCO$_2$*** at the census tract level, just above the social cost of carbon ($212/tCO$_2$), but range from -$286/tCO$_2$ to over $3500/tCO$_2$.

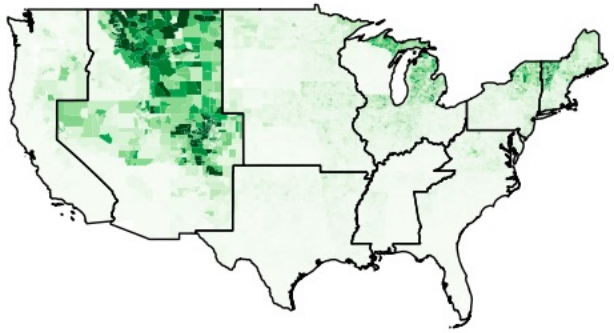
Distribution Investments:
Normalizing by emissions changes the picture



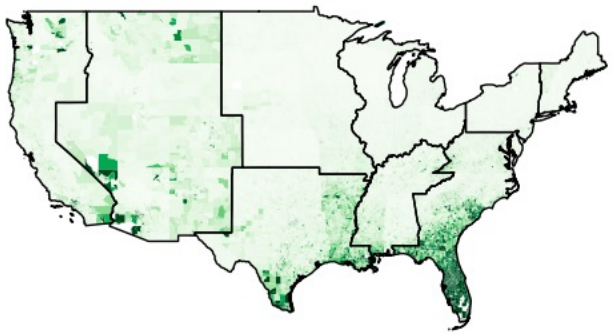
Price ($/kW)



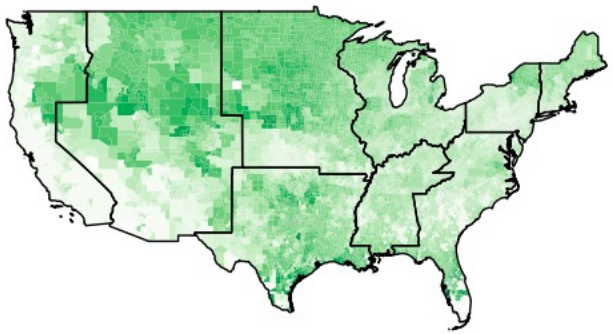
Upgrade Need (kW)



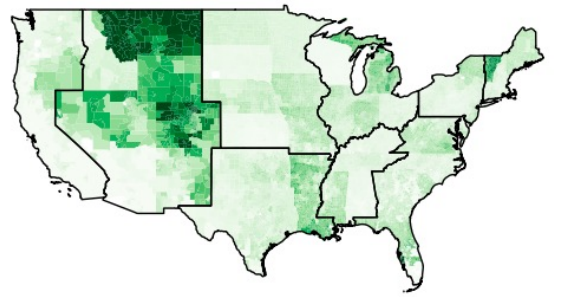
Investment ($)



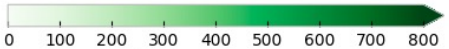
Price ($/kW/tCO$_2$)



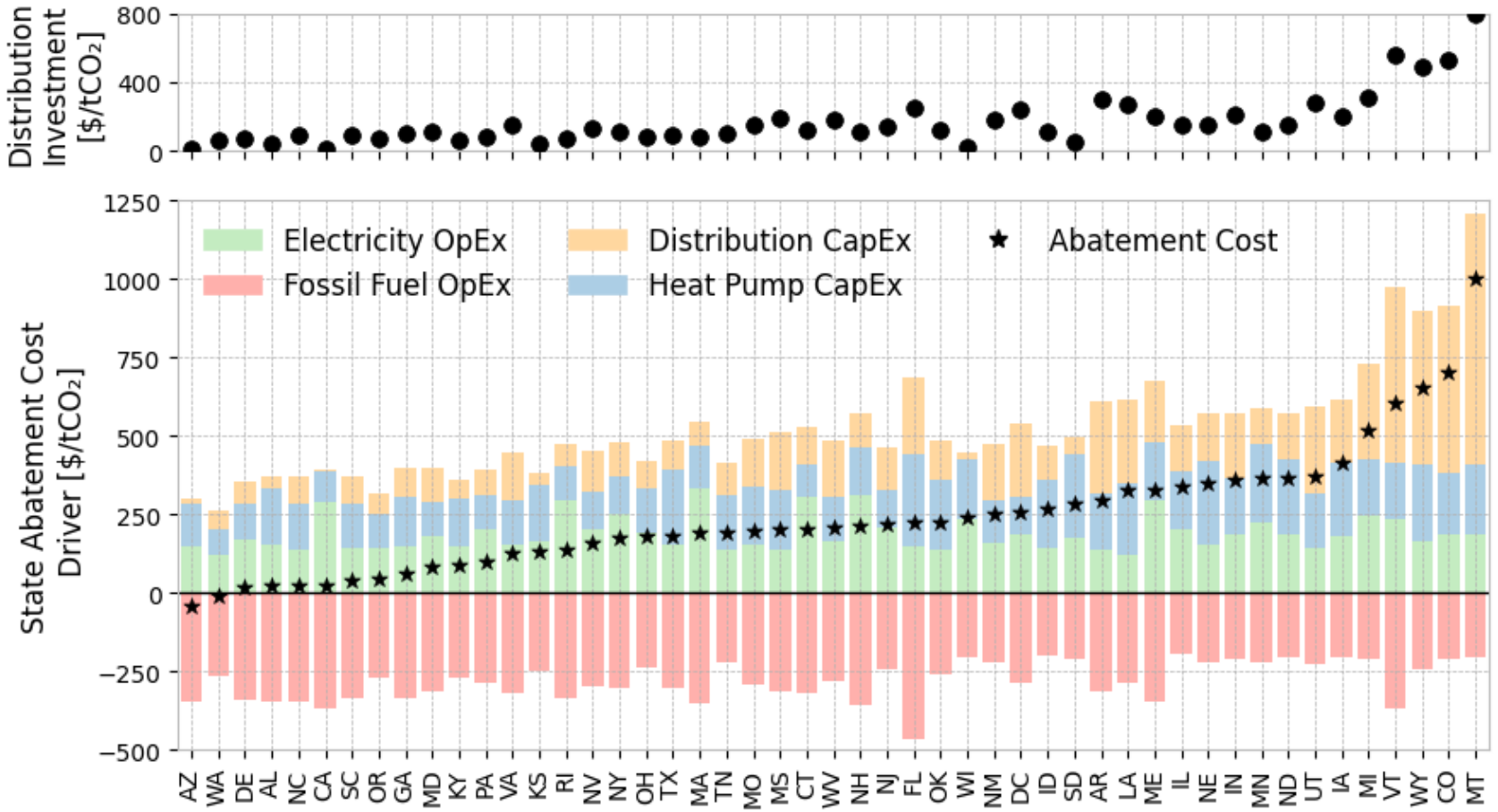
Upgrade Need (kW/tCO$_2$)



Investment ($/tCO$_2$)



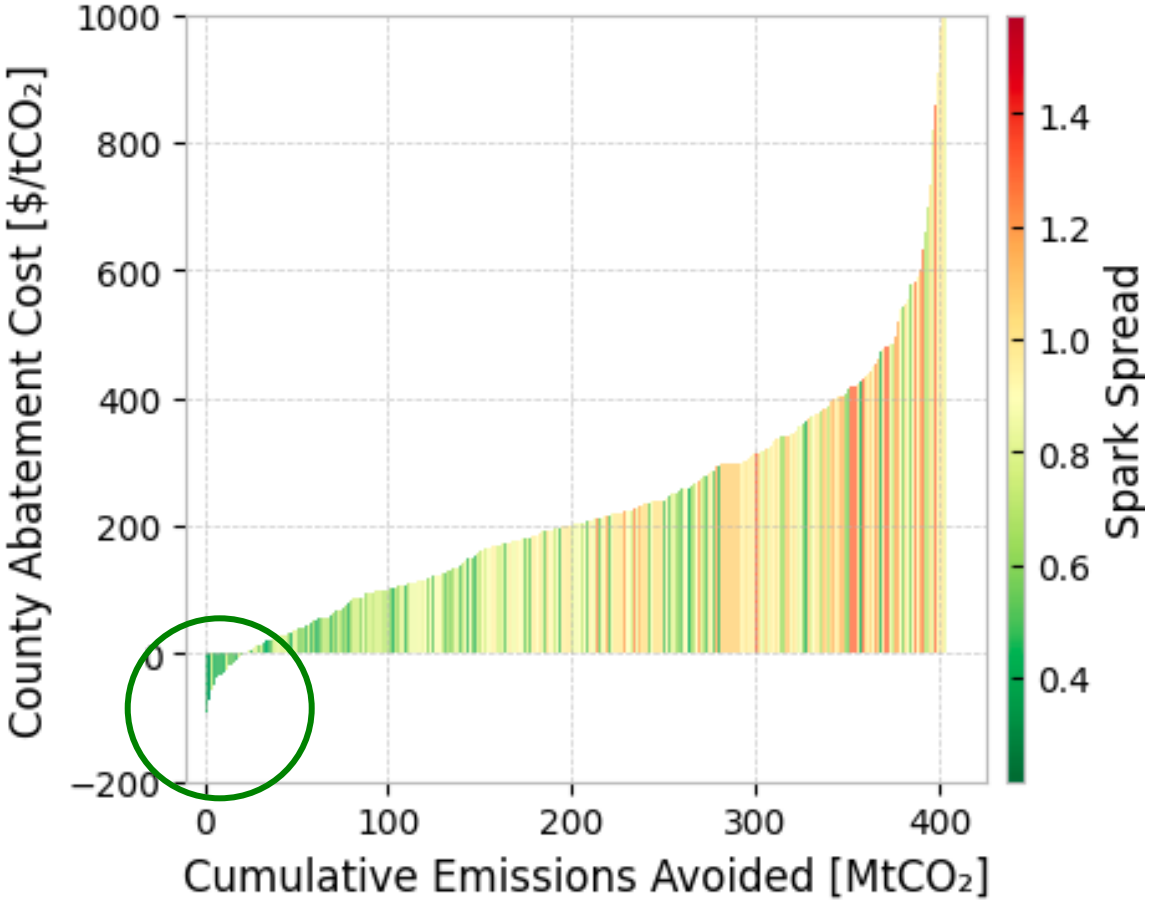
Drivers: Electrification of Fossil Heat in Buildings

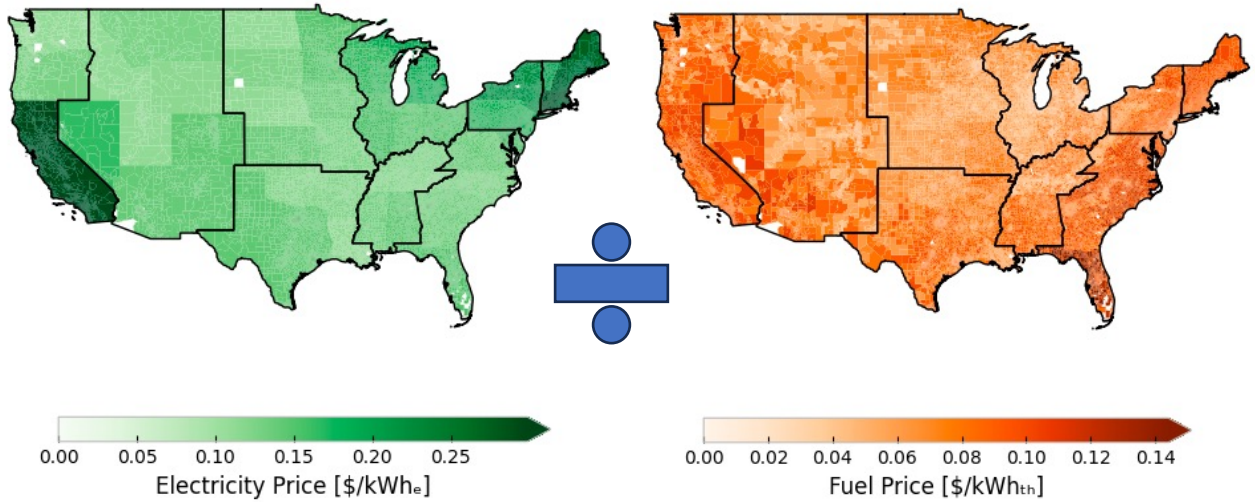


Distribution investment per unit of emissions avoided is the primary driver for high abatement cost states.

$$Abatement\ Cost = \frac{Cost_{clean} - Cost_{fossil}}{Avoided\ Emissions_{fossil}}$$

Drivers: Electrification of Fossil Heat in Buildings

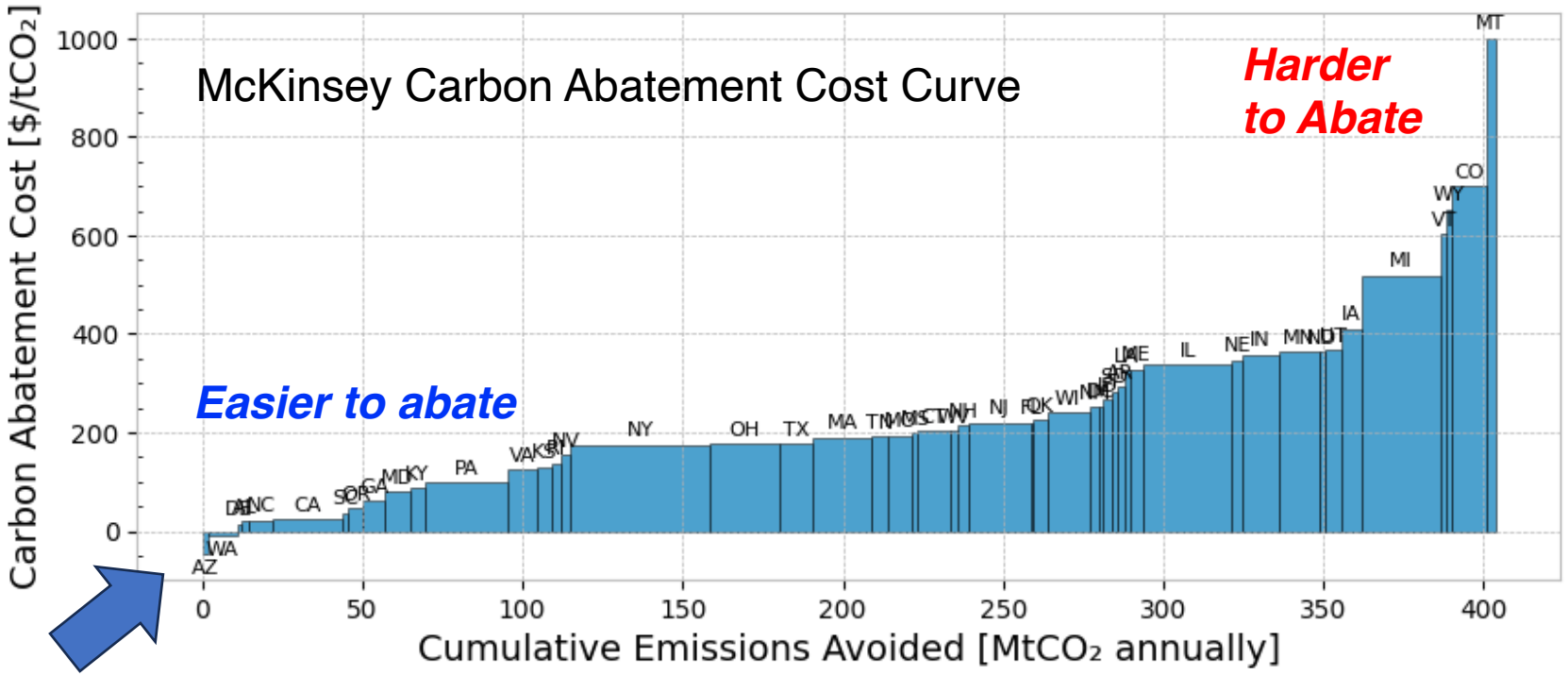


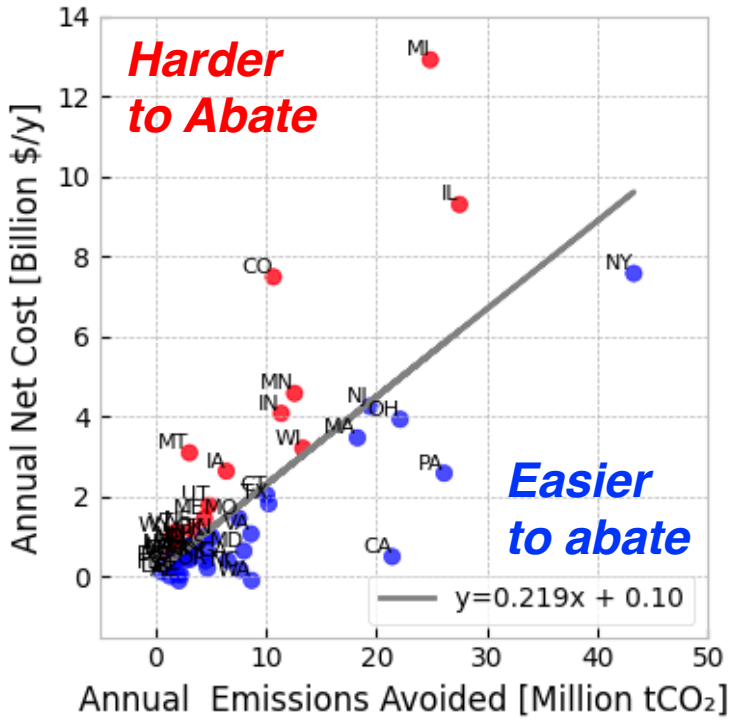


$$Spark\ Spread = \frac{Electricity\ Price}{Fuel\ Price\ * Efficiency}$$

- Counties with low abatement costs also tend to have low spark spreads.

Emissions-Weighted Abatement Costs



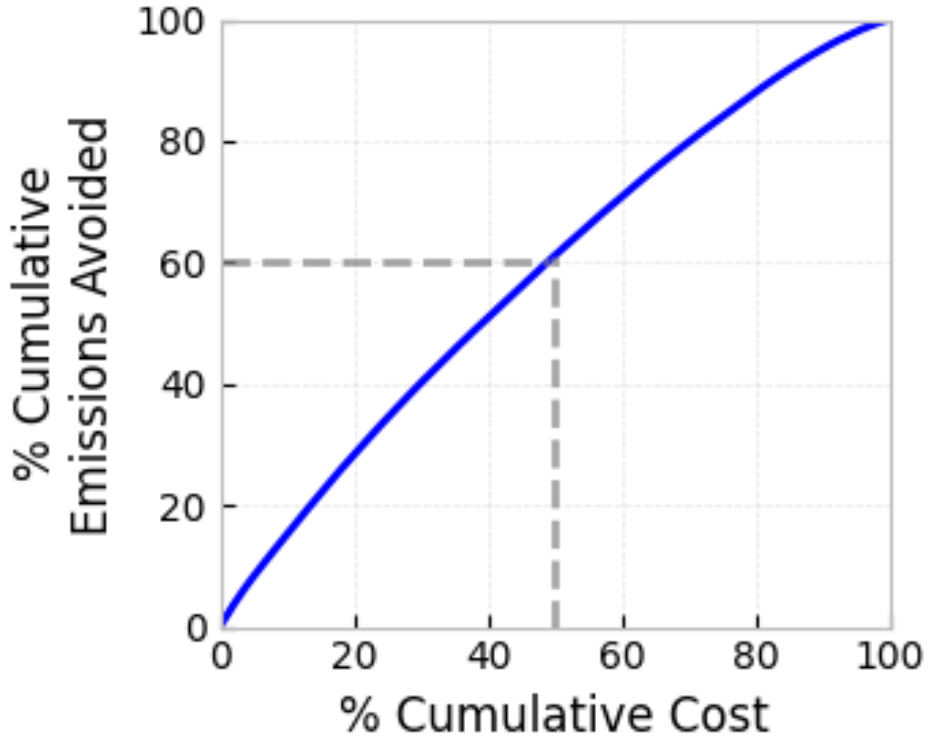


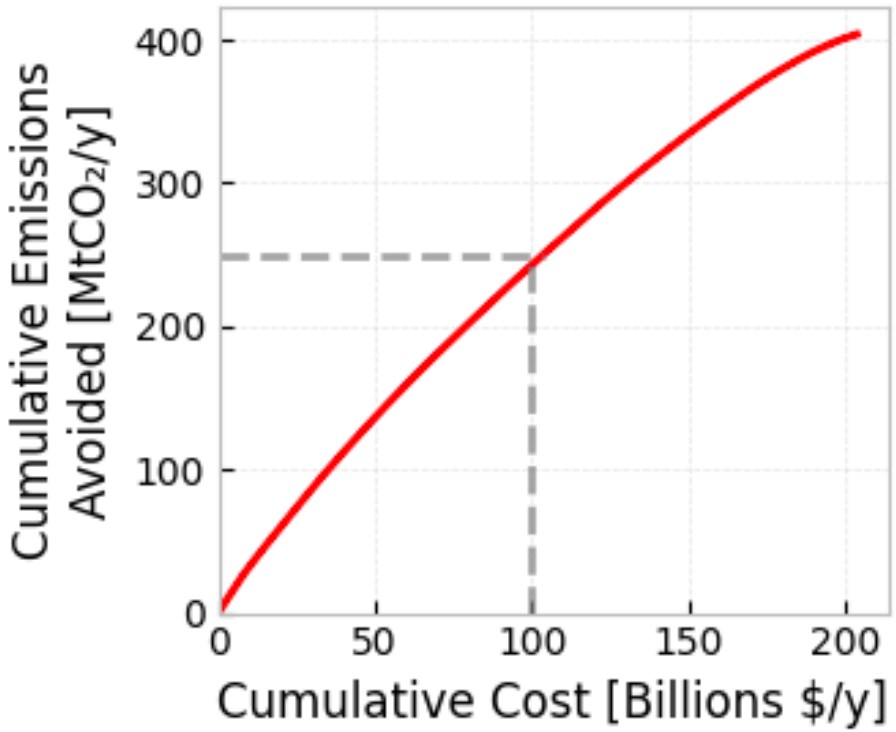
- ***Heat pump electrification in AZ and WA would save money!***
- Emissions-weighted average abatement cost by census tract is $230/tCO$_2$.

$$Abatement\ Cost = \frac{Cost_{clean} - Cost_{fossil}}{Avoided\ Emissions_{fossil}}$$

- Although MT, CO, WY have very high abatement costs, those states doesn't represent very many emissions.
- Targeting NY, PA, CA would avoid more emissions at lower cost.

Thresholds in Cumulative Emissions Avoided





- *For only 50% of the cost avoid 60% of the emissions! Buy now!* ☺

- Absolute values for a sense of scale

Success scenario: Abatement costs guide actions

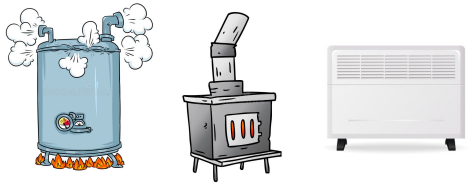
Success scenario:

Abatement costs guide actions

Negative (-) abatement costs
identify locations where heat pump electrification saves money.

Where should heat pumps or other clean heat technology be deployed now?

Deploy clean heat technology



Industrial facilities & census tracts

Large positive (+) abatement costs
identify difficult-to-decarbonize heat demands guiding innovation priorities.

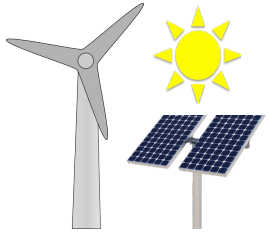
What clean heat tech innovations could decarbonize which heat demands?

Future work: sensitivity studies

Guide clean heat tech innovation

CapEx, OpEx, efficiency

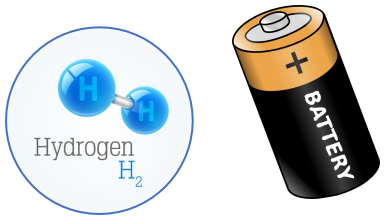
Weather data guides technology opportunities for decarbonization solutions



Wind & Solar Data

Past Work

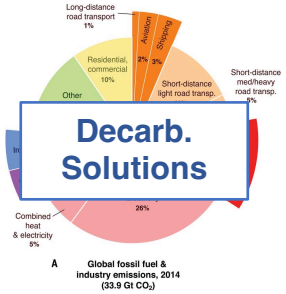
Wind and solar data to guide *energy storage* opportunities



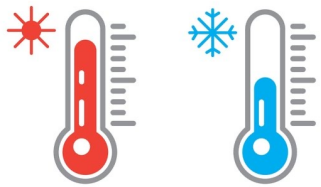
Energy Storage

Solutions

Load-following electricity



Current Work



Temperature Data

Temperature data to guide *heat pump* opportunities

Heat pump

Solutions

Net-zero emissions heat

Solving the Clean Energy Challenge

Reliable energy transitions given wind and solar droughts

Wind, solar, & hydro droughts

Critical materials

Water for Energy constraints

Subsurface constraints

Macro-energy systems to guide clean-tech innovation

Energy storage for load-following electricity

Clean heat for residential & industrial demand

Repurpose fossil infrastructure for decarbonization solutions

E.g. Coal to thermal energy storage. Gas to hydrogen storage.

Coordinate fossil phase-down and infrastructure transitions

Thank you for listening!

Clean Energy Systems Research

Jacqueline A. Dowling

Stanford | ENERGY
Postdoctoral Fellowship

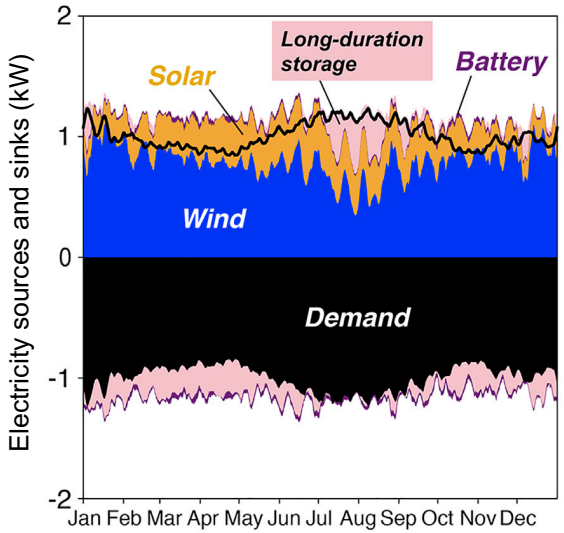
MERGING TALENTS
EMERGING IDEAS
eMERGE
SHAPING THE FUTURE
early-career Mobility & Energy Researchers' Group Exchange

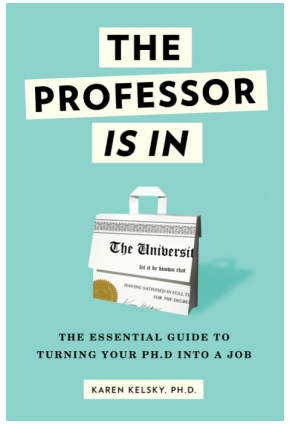
Analyze resource constraints. Guide technology innovation. Target decarbonization solutions.

Wind and solar constraints guide energy storage opportunities

Job market prep that helped me:

- Write papers you are excited about and present them at conferences!
- Coordinated with friends to gather job ads and deadlines in a google spreadsheet.
- Read example successful faculty application packages from friends.
- Went to workshops. Most useful tip for me: ***Organize your past and future research program into verb-driven thrusts.*** This made everything so much more concise.





Super helpful book that levels the playing field. I found it especially helpful for interview prep.

MERGING TALENTS
EMERGING IDEAS
SHAPING THE FUTURE